# ECONOMIC GEOLOGY

WITH WHICH IS INCORPORATED

THE AMERICAN GEOLOGIST

VOL. XVI SEPTEMBER–OCTOBER, 1921 NO. 6


## MOVING UNDERGROUND WATER AS A PRIMARY CAUSE OF THE MIGRATION AND ACCUMULATION OF OIL AND GAS.


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### INTRODUCTION.


OHIO STATE AGRICULTURAL LIBRARY MAY 26 1921


The success of the geological search for oil and gas, especially after the more obvious pools have been found, must depend upon the accuracy of the geologist's understanding of the processes by which these substances are accumulated into pools of commercial size.

The theory that oil moves up the dip of the rocks into the anticlines mainly on account of its buoyancy as compared with water still seems to have many adherents, in spite of the fact that it has repeatedly been shown[1] that the component of gravity tending to cause a globule of oil to move up the dip of the rocks, for the dips prevailing in a large number of the oil fields, is much less than the static friction opposed to its movement. Repeated experiments, also, by various investigators[2] have shown

[1] Munn, Malcolm J., "Studies in the Application of the Anticlinal Theory of Oil and Gas Accumulation," ECON. GEOL., vol. 4, pp. 141–157, 1909. Daly, Marcel R., "The Diastropic Theory: a Contribution to the Study of the Mechanics of Oil and Gas Accumulation in Commercial Deposits," Am. Inst. Min. Eng., Bull. no. 115, 1137–1157, 1916.

[2] Shaw, E. W., "The Rôle and Fate of Connate Water in Oil and Gas Sands" (discussion), Am. Inst. Min. Eng., Bull. no. 103, pp. 1449–1459, 1915.

that no movement takes place, even vertically upward through the sands, unless the liquids are agitated in some way or moving gas is present.

As a result of the inadequacy of the theory of pure gravitational migration, a number of geologists have suggested other causes for movement and accumulation. Johnson[3] has stated that it is probably necessary that a relatively large globule should form before movement can start because, on account of surface tension:

> . . . oil cannot move until the bubble grows so large as to extend a bud through one of the larger passageways into the adjoining chink between grains. Only a continuous invasion can make progress. It is a mistake to think of a passage of a series of bubbles as such. The resistance in that case would be so great that gravitation at least would be impotent except with very coarse deposits.

Johnson has also argued[4] that the squeezing of water out of the sediments during the process of compacting, as well as the expulsion of liquids on account of the generation of gas in the deeper rocks, would cause upward movement of the rock fluids together with any disseminated oil and gas which they might contain.

McCoy[5] is led, from the results of his experiments, to believe that, in general, oil does not migrate for great distances and is mostly accumulated near its source of origin, mainly by capillary forces.

Shaw and Munn, in several of their reports on the Appalachian fields, called attention to features which did not seem to be explained by the then prevailing theory of segregation due to

Johnson, Roswell H., "The Rôle and Fate of Connate Water in Oil and Gas Sands," Am. Inst. Min. Eng., Bull. no. 98, pp. 221–226, 1915. McCoy, A. W., "Some Effects of Capillarity on Oil Accumulation," *Jour. Geol.*, vol. 24, no. 8, pp. 798–805, 1916. Emmons, W. H., "Experiments on Accumulation of Oil in Sands (Abstract)," *Bull. Am. Assn. Petroleum Geol.*, vol. 5, no. 1, pp. 103–104, 1921. Rich, John L., Unpublished experiments.

[3] Johnson, Roswell H., "Water Displacement in Oil and Gas Sands" (Abstract), *Min. and Met.*, vol. 109, pp. 516–517, 1920.

[4] Am. Inst. Min. Eng., Bull. no. 98, pp. 221–226, 1915.

[5] *Loc. cit.*

buoyancy. Later, Munn developed the well-known "hydraulic theory."[6] Certain features of this theory, especially the idea that the location of the oil pools is due to bodies of oil becoming trapped and held—partly by capillarity—between advancing water currents, seem to have prevented its general acceptance, though Munn's work did much to advance the idea of the importance of moving water as an oil carrier.

More recently Daly[7] has urged that the movements of rock fluids caused by deformation are the most important causes of oil migration and accumulation. The fluids, including disseminated oil and gas, are supposed to be squeezed out of the zones of greatest compression and concentrated farther from the sources of thrust pressures in belts where the compression is less intense. Since the crests of anticlines, above the neutral zone, would be places of relative tension, the common association of oil with anticlinal structures is accounted for.

Shaw,[8] in connection with his discussion of a number of papers, has repeatedly mentioned and partly developed the idea that moving underground water, due to simple artesian circulation and to slow downward percolation of water into the great geo-synclines, has carried with it oil and gas which has been segregated in favorable places under the influence of selective buoyancy. He has suggested that, where water movement is relatively rapid, oil and gas may both be completely flushed out of the structure, while with a little less rapid movement gas, only, may be trapped—the oil being more readily carried along and flushed out by the water.

The writer acknowledges his indebtedness to Shaw, who, in conversation, first convinced him of the importance of the rôle of circulating water, and thereby furnished a key to an understanding of many peculiarities of the occurrence of oil and gas which he had noted, or which had been pointed out to him, but

[6] Munn, Malcolm J., "The Anticlinal and Hydraulic Theories of Oil and Gas Accumulation," ECON. GEOL., vol. 4, pp. 509–529, 1909.

[7] *Loc. cit.*

[8] Shaw, E. W., ECON. GEOL., vol. 12, pp. 610–628, 1917; Am. Inst. Min. Eng., Bull. no. 108, pp. 2428–2430, 1915.

which were not satisfactorily explained by the prevailing theories. On the basis of the ideas of Shaw and Munn, carried out to their logical conclusions, the writer has developed the theory of the hydraulic migration and accumulation of oil and gas which is explicitly stated and discussed in the following sections of this paper. In its broader aspects, the theory is a somewhat modified form of Munn's "hydraulic theory."

In order to put the essential points of the theory before the reader at the beginning, they are stated in summary form in the following section.

### SUMMARY STATEMENT OF THE THEORY.

The principal cause of the *migration* of oil and gas is the movement of underground water which carries with it minute globules of oil and bubbles of gas, possibly as fast as they are formed.

*Accumulation* results from the selective segregation of oil and gas, which, on account of their buoyancy, always tend to work their way upward[9] as they are carried along and are caught and retained in anticlinal or other suitable traps.

The nature of the trap necessary to cause accumulation depends on the rate of movement of the water and the corresponding texture of the sand or other medium through which it flows. Where the sands are porous and there is a strong hydraulic head, a sharp anticline with large closure is necessary to retain the oil—in fact, where the movement is especially rapid, even such a structure may be inadequate. Where the sands are fine and the water movement is slow, slight structural and textural variations are enough to arrest the movement of the oil and gas. Under such conditions broad, flat anticlines with very little closure, terraces, or even minor flattenings of the regional dip are enough to cause accumulation.

[9] Not necessarily up the dip, but up toward the roof of the containing reservoir.

## UNDERGROUND WATER CIRCULATION.

It would seem to be unnecessary to argue for the widespread movement of underground waters under the influence of gravity and differences of head, yet petroleum geologists, as a rule, appear to have ignored this movement. The well-known facts of artesian circulation through distances of hundreds of miles admit of no dispute.

Van Hise[10] has pointed out the exceedingly widespread nature of the underground movements, even through rocks which are much less pervious than those which furnish the well-known artesian water supplies.

Siebenthal,[11] in his study of the zinc and lead deposits of the Joplin region, brings out in a striking manner such extensive circulation and some of its results in the concentration of the ores.

All rocks are more or less pervious to water, though, of course, there are great differences in permeability and in the consequent rate of water movement through them. For the petroleum geologist it is important to bear in mind that no rock is so dense as to prevent entirely the passage of water through it.

The perviousness of the finer-grained rocks to water is greatly increased by increase of temperature, which lessens the viscosity of water and consequently increases its rate of flow through openings of capillary size. Van Hise[12] states that at 90° C. the viscosity is only one fifth what it is at 0° C. This means that at great depths, where temperatures are high, water finds its passage through relatively impervious rocks much easier than at the surface.

The general principles governing the circulation of underground water, especially in the more porous reservoir rocks, are well enough known so that the broader features of the circulation

[10] Van Hise, C. R., "Motions of Underground Waters," *Jour. Geol.*, vol. 8, pp. 730–770, 1900.

[11] Siebenthal, C. E., "Origin of the Zinc and Lead Deposits of the Joplin Region, Missouri, Kansas, and Oklahoma," U. S. Geol. Survey, Bull. 606, 1915.

[12] *Loc. cit.*

under any given set of conditions can be predicted with fair accuracy by the geologist.

## RELATION OF DISSEMINATED OIL AND GAS TO UNDERGROUND WATER CIRCULATION.

Suppose that a widespread bed of sandstone happens to lie between petroliferous shales. Whatever the origin of the oil, nearly all are agreed that, by one process or another, a considerable part of it will find its way out of the shales into the porous sandstone. All will probably agree, also, that it must enter the sandstone very gradually in the form of minute globules, probably of microscopic size.

Such a sandstone is almost certain to be a channel of water circulation. What will become of the oil after it enters the sandstone? Will its movement be controlled by buoyancy alone, irrespective of the water movement, or will it be controlled by the motion of the water into which it enters?

According to the old idea of up-dip movement on account of difference in specific gravity between oil and water, the tiny oil globule will work its way up the dip of the sandstone even though the dip be as low as 10 feet per mile, and even, so it has always been tacitly assumed, against a downward artesian flow of the water in the sand. In view of the results of repeated experiments and of the calculations mentioned above, is not this an absurdity?

The specific gravity of oil is so near to that of water that oil is very easily carried along in a water current, even if the movement is very slow, just as a piece of wood is carried along by a river. To expect a block of wood to float upstream on account of its buoyancy would be about equivalent to expecting a minute globule of oil to work its way up the dip in the face of an opposing water current.

If the oil globules are relatively large as compared with the size of the openings between the sand grains of the reservoir, there must be a lower limit of velocity beyond which the water current is unable to move them against the friction opposing

their motion. The same velocity of movement which would fail to carry a globule of a given size would, however, suffice to carry a smaller one, and so on down to the smallest sized globule that can be conceived.

Since the oil and gas globules as they are first formed and first enter the sand are undoubtedly exceedingly small, it is not necessary to suppose that an exceptionally rapid water flow is necessary for their transportation.

### EXPERIMENTS ON WATER CURRENTS VS. BUOYANCY AS A CAUSE OF OIL MIGRATION.

If the reader is inclined to doubt the efficiency of a current of moving water as compared with buoyancy alone in causing the movement of oil through water-soaked sands, let him try the following experiment:

Take two straight glass tubes ½ inch or more in inside diameter. Close the lower end of each with a tightly fitting cork. Then place in the bottom of each 6 inches or more of water-soaked sand (clean sand with diameters of grains ¼ to ½ mm.). Above this place a layer of oil-soaked sand, and above that another layer of water sand. Set tube No. 1 aside to permit buoyancy to do its work. Hold tube No. 2 in a vertical position and loosen the cork at the bottom sufficiently to permit the water to drip out slowly at the rate of about one drop per second. This will cause a slow current vertically downward through the tube.

In the writer's experiments[13] there was no movement in tube No. 1, even after several months and in repeated experiments. The water dripping from the bottom of tube No. 2 was mixed with oil after a very few seconds. By watching the tube closely with a hand lens one could see the globules of oil being carried downward in the water current. Larger globules which became lodged between sand grains were broken up into smaller ones by a process of "budding" and then carried downward.

[13] Oil of 28° B. was used. Lighter oils might rise more readily on account of buoyancy, but any general explanation of the migration of oil must hold for 28° oil as well as for that which is lighter.

In these experiments the rate of water movement between the sand grains was rapid as compared with that of ordinary artesian circulation, but it should be remembered that the work which it accomplished was much more difficult than that of merely transporting minute oil globules. In this instance the surface tension of the oil had first to be overcome in breaking the larger globules up into smaller ones, which were then carried vertically downward, directly against the force of buoyancy.

In the case of tube No. 1 the conditions were no less extreme, for the dip was 90° and the sand was coarser than most oil sands, yet there was no movement.[14] The element of time does not enter, for static friction is not a function of time. If static friction will prevent the movement of a body for one minute, it will prevent it for an indefinite time under like conditions.

Certain of Mills's experiments[15] have been cited to prove that accumulation will take place through the action of buoyancy alone, but, as pointed out by McCoy,[16] this occurred only with the lighter oils and in sands much coarser than most oil sands.

## CONDITIONS NECESSARY FOR THE SEGREGATION OF OIL AND GAS FROM A MOVING WATER CURRENT.

If oil and gas are being carried along in a moving current of underground water, what are the conditions necessary to cause their segregation and accumulation? In a broad sense, any condition which exerts a selective action on the oil and gas and retards their movement as compared with that of the water should cause accumulation. On a purely deductive basis, it would seem that any of the following conditions should satisfy the requirements: (1) an anticlinal trap; (2) a decrease in the size of the rock pores; (3) a decrease in the rate of water movement below a certain minimum which varies with other conditions. Below is a fuller analysis of each of these.

[14] Temperatures as high as 100° F. maintained for several days did not cause movement.

[15] Mills, R. Van A., "Experimental Studies of Subsurface Relationships in Oil and Gas Fields," ECON. GEOL., vol. 15, pp. 398–421, 1920.

[16] McCoy, A. W., (Discussion) ECON. GEOL., vol. 15, 680–682, 1920.

*The Anticlinal Trap.*—It is here that buoyancy is effective. As the minute oil globules are carried along through the sands, their buoyancy will cause them to take advantage of every opportunity to work their way upward toward the roof of the reservoir. Wherever, in passing between sand grains, an oil globule finds itself entirely surrounded by water it will rise to the top. This must lead to a concentration along the roof of the reservoir. Where a reverse dip is encountered, the oil, on account of this selective action of buoyancy, will gather under the roof of the trap. As the oil globules entering the trap coalesce into larger masses they are less easily moved than the single globules because of the cumulative buoyancy and the surface tension of the larger masses. When accumulation has once started in an anticlinal trap it tends, for the reasons just given, to continue until the trap is full.

*Terraces* may be looked upon as special forms of anticlinal traps. Where the water movement is *down* the dip, the writer can see no reason why there should be accumulation on a terrace, but experiments would be needed to prove this. Where the water movement is *up* the dip, and is so slow that, assisted by the gravity component of buoyancy, it is little more than able to move the oil with it, the flattening at the down-dip edge of a terrace might be enough to arrest the movement of the oil and gas and start an accumulation. This would tend to grow and to persist for the same reasons which were given for the growth and persistence of the pool in the anticlinal trap. This pool would grow from accretions added on the down-dip side and in time might extend for a considerable distance down the dip from the edge of the terrace.

In general, a terrace should be able to cause oil accumulation only where the movement of the rock fluids is comparatively slow, so that slight obstacles suffice to arrest the movement of the oil globules.

*Decrease in Size of Rock Pores.*—If oil is being carried along in a reservoir bed which pinches out into less pervious beds in the direction of movement, the oil and gas should be screened

out and accumulated near the end of the pervious bed. There are two reasons for this. One is the greater friction on the oil globules as the texture of the rock becomes finer; the other is the effect of capillarity which tends to prevent oil leaving coarse, water-soaked beds to enter finer ones.

Where the water movement happens to be up the dip, the accumulation would be on the up-dip end of the pinching reservoir bed. Where the movement is *down* the regional dip, however, the deduction would be that the oil accumulation should be at the down-dip end of the reservoir, unless there were anticlinal traps near the down-dip end, in which case most of the oil would doubtless be caught by them.

The idea of accumulation at the down-dip end of a pinching bed on a plane monocline where the movement of the water is downward is a deduction which will doubtless be quickly challenged, yet it is one which seems necessarily to follow from the principle that oil movement is due to hydraulic currents rather than to buoyancy alone.

*Decrease in Rate of Water Movement.*—Assuming a reservoir bed of uniform porosity, it may readily be seen that any condition which would decrease the rate of water flow until it became too small to move an oil globule through a rock of that particular texture would lead to an oil accumulation. Pools of commercial size might not, however, be formed because of the slow rate of accretion and also, perhaps, because the process would be self-limiting in that as soon as a certain proportion of the cross-section of the reservoir became clogged with oil, the rate of water movement through the remainder would thereby be increased, with the result that part of the oil would then be carried on.

The principal effect of decreased rate of water movement is probably to permit accumulation in very slight structural and textural irregularities, which would be ineffective if movement were more rapid.

### THE INFLUENCE OF FAULTS.

Where the water movement is up the regional dip, a fault may cause accumulation by acting in the same way as an ordinary

anticlinal trap, but, according to the deductions stated above, a fault may also cause accumulation on its up-dip side where the water movement is down the dip. It does this by serving as a screen or sieve, permitting the slow passage of water where the reservoir bed is offset against a less pervious bed, but holding back the oil in a way exactly analogous to that discussed above for a reservoir bed which pinches out down the dip.

Accumulation in such relationship to the fault would probably occur only in connection with strike faults so situated that escape of the oil along them or around their ends would not be possible. The most favorable place for accumulation would be on the up-dip side of a strike fault cutting a plunging anticline or anticlinal nose whose long axis is parallel to the dip. In general, a dip fault should not cause accumulation.

### FLUSHING.

Mills[17] has shown experimentally that a current of moving water in sand is capable of flushing oil out of an anticlinal trap even after it has gathered into a definite pool. The writer's experiments, referred to above, in which oil was readily carried downward through sand by moving water, would also lead one to expect that flushing would occur wherever the water current is sufficiently strong.

The flushing action of moving water, for a given velocity, would be considerably more effective in preventing original accumulation than it would in flushing oil out of a structure in which it had once accumulated, because, in the former case, the individual globules would be carried along one by one and there would be no opportunity for cumulative buoyancy or surface tension to act, whereas if oil is once accumulated in a trap, those forces must be overcome before it can be carried away.

Mills's experiments and the photographs accompanying them illustrate in a striking way a result of flushing which the writer had already deduced from a study of the principles of hydraulic accumulation, namely, that in the process of flushing the oil

[17] *Loc. cit.*

accumulated in the trap is displaced toward the lee side of the structure, on which side it may extend much farther down the dip than on the side from which the water comes.

This is the condition which the experiments show and which should be expected where a structure in which oil has previously accumulated is subjected to flushing as a result of later physiographic changes which increase the rate of underground water flow past it.

A very different result is to be expected where oil is accumulated in a trap past which water movement is very slow. Under such circumstances it should be expected that the oil and gas would first gather under the crest of the trap. Later accretions would be on the side from which the water comes. As a result, the oil pool should extend farther down the dip on that side.

### APPLICATION OF THE HYDRAULIC THEORY TO SIMPLE TYPE CONDITIONS WITH ILLUSTRATIONS FROM PROVEN FIELDS.

In order to test the theory and to compare its deduced consequences with the results of drilling, two simple type conditions, with illustrations, are considered below. Type 1 is a large artesian basin underlain by porous sands interbedded with petroliferous shales and having one rim (the intake rim) much higher than the other (outlet rim). The Big Horn Basin of Wyoming is an example. Type 2 is a coastal plain whose rocks dip gently seaward and comprise extensive sheets of sand between less pervious beds. The Gulf Coastal Plain of Texas–Louisiana is the type.

*Type 1. The Artesian Basin.*—In a large intermont basin, like the Big Horn Basin of Wyoming, there are ideal artesian conditions. The sands of the Cretaceous are exposed at relatively high altitudes along the borders of the basin, from which they dip steeply, with here and there a reversal, into the deeper parts of the basin, 5,000 to 15,000 feet below. Conditions at most places are favorable for the intake of meteoric waters at the outcrops, and in most of the basins the outcrops on the outlet rims are some thousands of feet lower than those of the same sands

on the intake rims. Under such conditions there is certainly a general and fairly rapid circulation of water through the basins.

The sands in the lower part of the Cretaceous series are interbedded with petroliferous shales which must have delivered, and probably still are delivering, oil to them. According to the theory here presented, this oil is carried along in the general water circulation until it encounters a structural trap capable of causing its selective segregation. In anticlinal traps close to the outcrop on the intake side, where the artesian circulation is free and rapid, the tendency would be toward flushing rather than accumulation. The connate water in the sands would be freshened and finally replaced by fresh water. The fresh water would be carrying little oil with it because the sands already would have been washed clean.

Not only would there fail to be accumulation of oil in the trap under these conditions, but any oil which might have accumulated under other physiographic conditions when the trap was farther from the outcrop or was subjected to less active water movement would tend to be flushed out.

Deeper down in the basin the water flow would be less rapid, partly on account of leakage from the roof of the reservoir,[19] and partly on account of the general diffusion of the flow through the whole area of the basin. As a result, accumulation in favorable traps, rather than flushing, would be the rule.

Obviously there would be every gradation from conditions near the intake outcrop, where even well-closed anticlines would be completely flushed and filled with fresh water, through those where structures with ample closure still hold a small pool of oil or gas close to the crest, but, in general, more extensive on the side away from the direction of flow, to structures in which there has been only accumulation and the oil is still associated with salty waters. It is probable, as has been suggested by Shaw,[20] that near the limit of complete flushing gas, on account of its

[19] Schlicter, C. S., "Motions of Underground Waters," U. S. Geol. Survey, Water Supply Paper, 67.

[20] *Loc. cit.*

greater buoyancy, would be retained on structures which were unable to hold oil.

Starting from the intake rim, the normal sequence in such a basin would be: anticlines completely flushed; anticlines holding only gas; anticlines holding gas and a little oil; anticlines holding oil and gas.

On the outflow side of the basin there would be a strong tendency toward the concentration of oil and gas. Even structures close to the outcrop should be productive, and strong closure should be unnecessary. Terraces and anticlinal noses would be likely to be productive. Oil-saturated sandstone or limestone should be common at the outcrop.

Where one such basin leads into another across a saddle, there should be a strong tendency toward the concentration of oil and gas in suitable structures on or near the saddle,[21] because such saddles would be in position to receive accumulations from the constant flow of oil-bearing water from one basin to the other. In the course of time much more oil would be brought to a structure so located than could possibly reach an anticline near the intake rim of a basin.

How do the above deductions compare with the results of drilling in artesian basins such as those described?

In the first place, they afford a logical explanation of Hewett and Lupton's more or less empirical law relating to "mountainward and basinward structures."[22] These authors noted that the anticlines nearest the mountains were, as a rule, barren, while those farther out in the basin were productive. They explained this condition as a result of the basinward structures having intercepted the oil in its up-dip migration from the center of the basin and cut it off from the structures nearest the outcrop.

Though this "law" has proved to be a useful generalization and has been applied to other fields, there are several exceptions to it where mountainward structures not so situated as to have

[21] Provided they are not so located as to be flushed by water from near-by outcrops.

[22] Hewett, D. F. and Lupton, C. T., "Anticlines in the Southern Part of the Big Horn Basin, Wyoming," U. S. Geol. Surv., Bull. 656, 1917.

their drainage intercepted by other anticlines nearer the center of the basin nevertheless contain no oil. Moreover, there are few of the barren "mountainward" structures which do not have enough "drainage area" tributary to them to have furnished at least a small pool of oil.

The fact that the sands of the barren mountainward structures, on being tested, were found to contain fresh or slightly brackish water is significant and indicates flushing, as has been noted by Emmons.[23]

A number of Hewett and Lupton's "mountainward structures" which are barren of oil in the coarse Cretaceous sands have proven productive in the less porous and deeper Embar sands—a fact which finds ready explanation under the theory here proposed, but does not accord with Hewett and Lupton's explanation, for a basinward fold which would cut off the oil drainage in one sand should be expected to do the same for the one next below.

The more porous Tensleep sandstone, beneath the Embar, carries a little gas and oil in some places, but, though not extensively tested, it is most commonly found to be flushed.

The anticlines in the Big Horn Basin which have proven productive in the Cretaceous sands are, in general, the larger ones farthest from the outcrops. The Elk Basin anticline rises well out in the basin toward its outflow end. The dome at Byron, nearer the outcrop, has produced a little oil from a lenticular sand at approximately the horizon of the oil at Elk Basin, and large flows of gas from a deeper sand. The Frannie dome, still nearer the outcrop, has recently been found to contain only water, in spite of the fact that it has ample area from which oil might have migrated up into it if the old idea of up-dip migration is correct. The productive part of the Grass Creek anticline is the part least readily flushed by artesian waters, as may be seen from an inspection of Hewett and Lupton's map.[24] On this anticline

[23] Emmons, W. H., "Geology of Petroleum," McGraw-Hill Book Co., New York, 1921, p. 138.

[24] U. S. Geol. Survey, Bull. 656.

the effects of flushing are remarkably shown in that wells on the north and northeast sides of the structure, nearest the outcrop, strike only water at levels above those at which oil is struck on the southeast end of the anticline. The Greybull dome also shows an unsymmetrical arrangement of oil and gas, which is probably due to partial flushing.

A number of anticlines round the borders of the Laramie Basin have proven barren on account of flushing, but the Rock Creek structure, in the saddle at the outlet of the basin, is proving to be a rich oil field. A fault along the west side of the basin in this vicinity has thrown the Cretaceous sands deep down below the surface, so that there is no opportunity for flushing from the west side. On the east side of the saddle the outcrops are not close to the Rock Creek structure. As was stated in preceding paragraphs, a structure located like Rock Creek near the outlet of a basin should receive more than the ordinary amount of oil.

In this connection it is suggested, as a working hypothesis, that the remarkable productivity of the Salt Creek field may be due to the fact that it is located near a point where the combined artesian flow from all the artesian basins of central Wyoming drains out eastward through the gap between the Big Horns and the Laramie and Casper Mountains. At an earlier stage of the physiographic development of the region the passageway in the oil sands across this gap was considerably more extensive than now. The Salt Creek structure is located far enough from the outcrops of the producing sands, and in such relation to the nearest of them, that recent flushing action can not have been intense.

In connection with his description of the Powder River field of Wyoming, Wegemann[25] discusses the artesian circulation of oil and water and, on that basis, argues that the principal oil accumulation should be on the east side of the dome. He suggests that the distribution of the water and oil in the Dakota sandstone, where the water level is higher on the west side of the dome, may be a result of the artesian circulation.

[25] Wegemann, C. H., "The Powder River Oil Field, Wyoming," U. S. Geol. Surv., Bull. 471, pp. 56–75, 1912.

In Montana a great deal of the unsuccessful drilling has been done on anticlines which are in position to be completely flushed by the strong artesian circulation which there prevails.

The new Cat Creek field[26] presents a number of features which suggest that its productivity may be due to the fact that faults cutting across the structure may have interfered with the flushing action and have permitted accumulation behind the barriers thus formed, as has been suggested by Reeves.[27] Another feature which accords with the flushing hypothesis is the fact that oil is being found at a much lower level on the north, or leeward, side of the structure than on the south side.

Huntley[28] discusses the probable results of widespread water movements in the Dakota sand of Canada and the United States and suggests that the enormous concentration of asphaltic materials in the Athabasca tar sands may be the result of this movement, since it occurs on a low anticline at the point of outflow of the Dakota basin, where the sands are becoming finer and less pervious than they are under most of the basin.

It seems to the writer that the features of oil and gas accumulation in the Dakota sand, as described by Huntley, furnish strong evidence in favor of the idea that oil and gas may be carried freely and for long distances in an artesian water circulation.

Besides the oil fields of the Rocky Mountain region, two other great oil fields of the United States are associated with major geo-synclinal basins—namely, the Appalachian field and the Mid-continent field of Oklahoma–Kansas.

In the Appalachian field the outcrops of the oil-bearing formations in the mountains are considerably higher than on the west side of the geo-syncline, therefore conditions are favorable for westward and northwestward artesian circulation. Even though

[26] Lupton, C. T. and Lee, Wallace, "Geology of the Cat Creek Oil Field, Fergus and Garford Counties, Montana," *Bull. Am. Assn. Pet. Geol.*, vol. 5, no. 2, pp. 252–275, 1921.

[27] Reeves, Frank, U. S. Geol. Survey Press Bulletin published in *Oil and Gas Journal*, Mar. 18, 1921, pp. 68, 72.

[28] Huntley, L. G., "Oil, Gas, and Water Content of Dakota Sand in Canada and United States," Am. Inst. Min. Eng., *Trans.*, vol. 52, pp. 329–349, 1916.

a particular reservoir bed plays out before reaching the western side of the basin, the universal perviousness of all rocks would permit a slow westward circulation. Irregularities, lensing, and pinching out of the oil-bearing sands westward have interfered with free circulation, as has also the little understood condition which has resulted in the apparent dryness of certain sands in the bottom of the geo-syncline. As a result, the factors governing the occurrence of oil in this region are very complex, and in much of the area the texture of the sands seems to have more significance in determining the location of oil pools than does structure. Nevertheless, it is noteworthy that the bottom of the geo-syncline is in no way avoided by the accumulations of oil—in fact, it is one of the richest parts of the whole field. This should not be so if the oil is concentrated by up-dip migration due to buoyancy. If, on the other hand, it is accumulated by the agency of circulating water, there is no reason why minor structures or favorable sand textures in the bottom of a geo-syncline should not be as productive as in any other situation except, perhaps, near the outflow side of a basin.

The fact that many of the oil-producing sands thin out and disappear in the region of the bottom of the geo-syncline[29] is an excellent reason, according to the hydraulic theory, why this region should be especially rich in oil accumulations; it would be here that the oil would be screened out and held in the terminal portions of the sand reservoirs while the water slowly filtered through the less porous rocks toward the west.

On the intake side of the Appalachian trough many, if not all, of the sands which are productive in the trough carry fresh water to considerable depths. On the outflow side, in parts of Ohio, for instance, the sands carry salt water almost to their outcrop and in a number of places are saturated with oil at the outcrop and yield oil in paying quantities at shallow depths, in some places within ½ mile of the outcrop.

Another great oil-producing region of the United States—the Mid-continent field of Oklahoma–Kansas—is situated on the out-

[29] Clapp, F. G., *Bull. Geol. Soc. Am.*, vol. 28, 1917, p. 563.

let rim of a broad geo-syncline whose intake rim lies, in general, 3,000 to 4,000 feet higher than the outlet rim. This is ample cause for a distinct artesian circulation from west to east. Is it not significant that this region of *supersaturation* with oil and gas should lie in the natural zone of concentration on the outflow side of this great artesian basin?

The rocks of the Paleozoic geo-syncline under discussion are not nearly so porous as the Dakota sandstone, which is known to carry a free flow of artesian water across a geo-syncline of similar size farther north, but they can not be entirely impervious, and, with nearly 4,000 feet of head, it does not seem reasonable that there should not be an important and constant, though slow, eastward movement.

The movement on the eastern side of the geo-syncline would be *up* the dip and would be very slow, so that slight interruptions of the general dip would be sufficient to arrest globules of oil and gas being carried along with the water. Low anticlines, terraces, and minor flattenings would be enough to cause accumulation, especially in the less porous rocks. Moreover, on account of the slow movement, such accumulations would be augmented on the down-dip side, so that the present relation of the productive area to structure—that is, extending farther down on the western slope than on the eastern—would prevail.

As in Ohio, the salt water in the sands comes close to the outcrop in this area, and saturated sands at the outcrop are by no means rare.

No matter what the conditions of artesian circulation may be, there can be no accumulation of oil without an adequate source of supply. The acceptance of the hydraulic theory of migration does not in any way lessen the importance of the rich Cherokee shales as the ultimate source of much of the Mid-continent oil. Nor is it necessary, under the hydraulic theory, to suppose that the oil has migrated for great distances into the structures of the Mid-continent field, though some of it may have done so. A total fluid movement of a few miles under the influence of the artesian circulation would probably be enough to cause notable

accumulations in a region like this where the amount of oil supplied to the sands from the adjacent shales is doubtless relatively large.

*Type 2. The Coastal Plain.*—The coastal plain of Texas–Louisiana may be taken as a type of coastal plains in general. On it the rocks dip gently seaward, but the dip is interrupted in places by low anticlines and by faults.

The general circulation of the underground waters is down the dip toward the coast, as is shown by the fact that fresh artesian water is obtained at many places near the sea at depths far below sea level and in beds originally deposited in salt water.

This circulation implies some upward escape for the waters beneath the Gulf of Mexico, partly, perhaps, along faults, partly by leakage through the beds overlying the water-bearing strata.

There would be a tendency for this seaward circulation to be counterbalanced, in part, by the landward flow of water squeezed out of the sediments in the process of compacting, as urged by Johnson,[30] but that such landward circulation is not dominant is proven by the presence of fresh artesian water below sea level and by the lack of evidence of abundant upward escape of salt water along the coasts.[31] Probably the main effects of compacting occur at a very early stage.

On account of the lack of ready outflow, the artesian circulation beneath a coastal plain must, in general, be much slower than that of an artesian basin on the land, especially if the latter has strong differences of head on the two sides.

Oil supplied to the sands of a coastal plain series of rocks would be carried seaward with the general artesian circulation. Close to the outcrop and, where the sands are very porous, for a considerable distance seaward the flushing action of the water would be sufficient to prevent accumulation of oil. At greater depth and greater distance from the outcrop the upward escape of water through leakage of the reservoir roof would decrease

[30] Johnson, Roswell H., "The Rôle and Fate of Connate Water in Oil and Gas Sands," Am. Inst. Min. Eng., Bull. no. 98, pp. 221–226, 1915.

[31] Shaw, E. W., "The Absence of Water in Certain Sandstones of the Appalachian Oil Fields" (discussion), ECON. GEOL., vol. 12, pp. 610–628, 1917.

the rate of flow in the sand to a point where accumulation could take place. Also, at greater distances from the outcrop much more oil-bearing water would be carried past a given structure, so that there would be much better opportunity for the concentration of the oil into large pools.

Since, in general, the accretions of oil to a gathering pool would be from the direction of the outcrop of the sands, there should be a tendency for the pools to be located on the outcrop sides of anticlinal structures instead of on the basinward sides as is the case in the Mid-continent fields. This tendency might be overbalanced where the water movement is especially rapid, so that it would produce a displacement of the oil pool such as that illustrated by Mills's experiments and photographs previously referred to.

If the general seaward dip of the rocks is interrupted by strike faults, especially if they happen to cut across plunging anticlines with their axes parallel to the dip, oil pools should gather on the outcrop, or up-dip, sides of the faults, because that is the direction from which the oil is supplied.

To what extent do the peculiarities of location of the coastal plain oil fields bear out the above deductions?

In the Caddo field of Louisiana the principal accumulations of oil and gas are on the north and northwest sides of the anticlinal structures—the sides where oil would first be arrested by them as it is carried downward in the prevailing coastward artesian circulation.[32] Matson noted this feature of distribution and explained it as above.

In the DeSoto-Red River field of Louisiana[33] the principal accumulations are on the north and northeast sides of the anticlines and north of the Gusher Bend fault. With reference to this, Matson and Hopkins say:[34]

[32] Matson, George C., "The Caddo Oil and Gas Field, Louisana and Texas," U. S. Geol. Surv., Bull. 619, 1916.

[33] Matson, G. C. and Hopkins, O. B., "The De Soto-Red River Oil and Gas Field, Louisana," U. S. Geol. Surv., Bull. 661, pp. 101–140, 1917.

[34] P. 125.

The gas and oil in the DeSoto-Red River field were probably accumulated under hydraulic pressure. This hypothesis is supported by the relations of these substances to the structure and by the occurrence of the oil in very productive pools of small area. The amount of oil in these pools is too great to be satisfactorily explained by assuming a local source on the flanks of the gentle folds that exist in this region.

And again:[35]

. . . There can be little doubt that the oil in the larger pools has been brought to its present position, in part at least, by movements of the water through the sand, and it will be observed that the producing areas lie where the circulation would be first impeded by the change in structure.

They further suggest[36] that, on account of certain features of the sands, the circulation of the water probably came from the northeast:

. . . This circulation of the water from the northeast would favor the accumulation of oil on the northeast side of the folds, whereas circulation from the northwest, such as clearly occurred in the Caddo field, would favor accumulation on the northwest side of the folds and would present conditions that were unfavorable for large pools on the east side, where the most productive areas in the DeSoto-Red River field are located.

Bates[37] has pointed out the close relation of some of the richest parts of this field to the Gusher Bend fault. It is significant that the rich oil pool is on the north side of the fault, as should be expected if the oil were carried in the artesian circulation. This condition is the reverse of what should be expected if buoyancy is the controlling cause of migration, for, were that true, the principal accumulation should be on the seaward, or down-dip, side of the fault.

In the Corsicana field of Texas it appears that textures of the sands have a very important, if not controlling, effect on the location of the oil accumulations. From the published descriptions

[35] P. 127.

[36] *Idem.*

[37] Bates, Mowry, "A Concrete Example of the Use of Well Logs," *Am. Inst. Min. Eng.*, Bull. 137, pp. 979-986, 1918.

of this field the writer is unable to determine the bearing of conditions there on the problem under discussion.[38]

Under the conditions prevailing near the seaward margin of the coastal plain, there would be a strong tendency for the water to rise toward the surface along any fracture zones which would permit upward movement. At that distance from the outcrop the artesian circulation would not yet have freshened the water in the deeper sands. There would, therefore, be an almost unlimited quantity of brine which might rise toward the surface along any fractures which gave it passage. If this brine were carrying with it oil and gas, as it would be almost certain to do, the conditions would be favorable for the precipitation of the salt by the evaporation of the water into the gas in the way suggested by Mills and Wells.[39] If such proves to be the true cause of the coastal salt domes, the occurrence of oil in large quantities around them finds ready explanation, for the domes furnish ideal traps for the oil brought to them in disseminated form by the deep artesian circulation.

### POSSIBILITY OF DOWNWARD MIGRATION OF OIL AND GAS.

If oil globules are carried along in the general water circulation, it is easily possible for oil to migrate downward across the strata, provided there are passages which permit the water circulation to take such a course.

A number of instances have been described where oil clearly must have migrated downward in some manner. Under the theory of movement on account of buoyancy this was difficult to explain. Where the movement was only for short distances, capillarity offers a more satisfactory explanation.

[38] It is highly desirable that some of those who have access to unpublished information on details of the coastal plain fields should put them on record for their bearing on the problem here presented.

[39] Mills, R. Van A. and Wells, Roger C., "The Evaporation and Concentration of Waters Associated with Petroleum and Natural Gas," U. S. Geol. Surv., Bull. 693, pp. 89–95, 1919.

EFFECT OF MOVEMENT OF ROCK FLUIDS INDUCED BY DEFORMATION.

In a suggestive paper already referred to Daly has urged the importance of the movements of the rock fluids induced by the compressions and tensions accompanying deformation as the leading cause of the migration and accumulation of petroleum.

In so far as deformation actually causes rearrangements of the rock fluids, it would, according to the principles underlying the hydraulic theory, be an adequate cause for oil migration and accumulation. The oil and gas would be carried along in the moving rock fluids in the same way whether the movement were due to deformation or to simple artesian flow, and the laws of accumulation would be the same.

The writer believes that movements due to deformation are of minor importance as a general cause of the world's oil pools, because such movements are short-lived and sharply localized.

EFFECT OF FLUID MOVEMENTS DUE TO COMPACTING.

This subject has already been touched upon in the discussion of coastal plains. It was there shown that at present, except, perhaps, for some of the youngest rocks now in process of formation, it is subordinate to artesian flow. Its effect, therefore, must be mainly to reduce the velocity of that flow without counteracting it.

At some stage of the compacting of the sediments large volumes of water must be squeezed out of them and must carry along whatever oil and gas has been formed up to that time.

On the coastal plain of the United States, however, the rocks in which the oil is found have been subjected to artesian conditions for a long period since most of the compacting took place. This must have modified and more or less rearranged any oil accumulations resulting from the first water movement.

In the older fields, away from the coastal plains, as, for example, in the fields of Wyoming, the geological history has been so complex and the stages of uplift, tilting, and folding have been so numerous and so widely spaced in time that it would be futile to seek for a detailed explanation of the present arrange-

ment of the oil pools in any postulated movements of the rock fluids at the remote time of original compacting.

In so far as the causes of movement of the rock fluids suggested by Daly and Johnson have been effective, their results will be algebraically combined with those of the ground waters circulating under the influence of gravity.

### STATUS OF THE ANTICLINAL THEORY.

It appears that the anticlinal theory, in so far as it implies that buoyancy is a prime cause of the movement of oil through rocks, is founded on a false premise. Nevertheless, the fact remains that most of the world's oil so far discovered is on anticlinal structures. Like many others, the anticlinal theory in its original form was a half-truth.

Buoyancy, it appears, though unable of itself to move oil through sands as fine as the ordinary oil sands, is the agency which, by its selective action on oil and gas moved through the sands by other agencies, causes the segregation and accumulation of these substances in anticlinal and other suitable traps. Buoyancy, however, is not the only force which causes segregation. Capillarity is also effective.

Since anticlines are the simplest and most common traps, the success of the anticlinal theory in practice seems to have blinded most geologists to the fundamental fallacy on which it is based.

HOBART, N. Y.

# THE MARBLE BAY MINE, TEXADA ISLAND, BRITISH COLUMBIA.[1]

VICTOR DOLMAGE.

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## INTRODUCTION.

The Marble Bay Mine, situated near the northern end of Texada Island in the Gulf of Georgia, is the oldest producing mine in the coast section of British Columbia, having produced high-grade copper ore since 1899. It also has the distinction of being the deepest mine in this district, having now reached the seventeenth level, which is more than 1,500 feet below the surface and about 1,450 feet below sea level, a fact all the more interesting because the mine is in limestone throughout its depth and only about a quarter of a mile from the sea shore. It has for a long time attracted more than ordinary attention from economic geologists by being one of the first mines to produce large quantities of bornite from relatively great depths, and thus to contradict the one time firmly rooted but erroneous theory that bornite was a definitely superficial mineral, and could not

[1] Published by permission of the Director, Geological Survey of Canada, Ottawa.

persist below shallow depths. At a more recent time it played a similar role in the discussion regarding the primary nature of chalcocite, which also occurs plentifully in all levels of the mine, even the very lowest.

Apart from its historic interest the mine has a complex and somewhat unusual association of minerals, having over thirty mineral species. The interest in the geology of the mine has been increased owing to the recent discovery on the seventeenth level of a large stock of granodiorite. This rock does not occur elsewhere in the mine, and is thought by the writer to be the source of the solutions which produced the ore.

*History.*—Copper was known to occur in the marbles of the northern portion of Texada Island as early as 1886, but not until William Christie, of Toronto, came into possession of the property was anything done to prove their value and extent. In 1897, after considerable preliminary surface work, a shaft was begun, which in 1899 had reached a depth of 140 feet and had disclosed a rich body of ore to that depth. The property then passed into the hands of J. J. Palmer, of Toronto. The shaft was continued in 1901 to a depth of 260 feet, and considerable quantities of rich ore were extracted, some of which was treated in a small smelter situated about a mile east of the mine, the remainder being shipped to the Ladysmith and Tacoma smelters. The ore extracted up to this time yielded $65,000, which was about equal to the amount thus far invested in the property. During this, and a slightly later stage of the mine's history, the theory of the superficiality of bornite, the principal ore-bearing mineral, was having a disparaging influence on the value and future prospects of the mine. Several prominent mining engineers examined the mine and gave adverse reports based on that theory. In spite of these reports, and partly on the advice of W. M. Brewer, the property was purchased in 1901 by its present owners, the Tacoma Steel Co. of Seattle, for a price approximating $150,000, to be paid by royalties on the ore extracted from the mine. The shaft was continued, encountering such large bodies of rich bornite ore that the royalties were sufficient

to pay the total purchasing price within two years from the date of sale. Development has continued steadily ever since, but though several rich ore bodies were discovered and mined, they were not continuous one with the other and were often found only after much expensive development work, which used up a large proportion of the profits. Work is now confined largely to the seventeenth level, and, though small bodies of ore have been found, they are not of sufficient size to bear the cost of extraction under present prices of copper.

*Previous Work.*—The geology and mineral deposits of Texada Island have been fully described by R. G. McConnell[2] of the Geological Survey of Canada. His report includes a geological map of the whole island and maps on a scale of 2,000 feet to the inch of the copper belt at the northern end of the island and of the iron belt on the west coast. Considerable information on the Marble Bay Mine has also been published in the annual reports of the Department of Mines of British Columbia, chiefly by W. M. Brewer, who has watched the development of the mine from its beginning. Mr. Brewer has also published an article on "The Origin of the Bornite Ores of Texada Island."[3]

The writer is indebted to Mr. Brewer for the historic facts here related, and also to D. E. Stephens, the present local manager of the mine, who rendered every possible assistance during the time spent by the writer on the property.

*Summary.*—The Marble Bay Mine is a high-grade copper mine of the contact metamorphic type, yielding an ore composed largely of bornite and carrying from 5 per cent. to 10 per cent. of copper and appreciable gold and silver. It has now reached the seventeenth level and the ore, though not so abundant in the lower levels, is essentially the same composition as throughout the mine.

The ore bodies are in a thick limestone formation nearly flat-lying and intercalated in a thick series of volcanic rocks belonging to the Vancouver Group, which is one of the most extensively

[2] McConnell, R. G., Geol. Surv. Can. Memoir 58, 1914.
[3] *Journal Can. Min. Inst.*, Vol. VII., 1905, pp. 172.

developed formations in British Columbia. The limestone, called the Marble Bay formations, is intruded by bodies of quartz-diorite and granodiorite, which belong to the Coast Range Batholith, and also by a number gabbro-diorite stocks and porphyrite dikes and sills, which McConnell believes to be a late phase of the batholithic invasion. The ore bodies of the Marble Bay and other neighboring mines are closely associated with these basic intrusions, and in McConnell's opinion the ore originated in the magma, which formed these dikes and stocks, particularly the latter.

However, since Mr. McConnell's work the ore bodies have been followed down from the thirteenth to the seventeenth level, where they come into contact with a large mass of granodiorite of presumably Coast Range batholith age, and the writer has concluded from this fact, as well as from several others, that the ore of the Marble Bay deposit originated in this granodiorite and not in the basic intrusions.

There is in the mine much chalcocite which is thought by the writer to be of primary origin. There are also, however, considerable chalcocite, native silver, covellite and serpentine which are thought to be formed by surface solutions. As the deposits are now below sea level, where surface waters would not be likely to circulate, it is thought that the enrichment took place during a pre-glacial period, when the deposit stood above sea level, and that afterwards it was submerged to its present position, and thus protected from the action of the Pleistocene glaciers.

## ROCK FORMATIONS.

The rock formations in the vicinity of the Marble Bay mine consist of: (1) a thick series of volcanics called by McConnell[4] the Texada Formation, which may be correlated with the Vancouver Volcanics of Dawson[5] and Clapp;[6] (2) a thick Marble

[4] *Op. cit.*, p. 21.

[5] Dawson, G. M., "Report on a Geological Examination of the Northern Part of Vancouver Island and Adjacent Coasts," Geological and Natural History Survey of Canada, 1887.

[6] Clapp, C. H., Geol. Surv. Can., Mem. 51, 1914. Clapp, C. H., Geol. Surv. Can., Mem. 96, 1917.

Bay Limestone, which lies conformably in the Texada formation and is of lower Jurassic or upper Triassic age; and (3) the granodiorite and quartz-diorite intrusions of the Coast Range batholith of upper Jurassic age. Besides these there are a number of stocks and dikes composed of porphyrites and gabbro-diorite, which McConnell considered to be a late phase of the batholithic intrusion, but some of which the writer believes to be feeders and off-shoots of the volcanic rocks which underlie and overlie the limestone.

The Texada Formation is a part of the Vancouver Volcanics which form the greater portion of the Vancouver Group, a series of immense thickness and wide distribution throughout western British Columbia. The Texada formation underlies virtually the whole of Texada Island, except three small areas of limestone, four of granodiorite and three small basins of Cretaceous sediments. It is several thousands of feet thick. It comprises a variety of volcanic rocks, including much andesite and andesite porphyry, also basalt, diabase, augite-porphyrite, hornblende-porphyrite and some diorite. These rocks are seldom fresh. They usually contain a large amount of secondary chlorite and epidote, which gives them a dull greenish color. They form a series of superimposed flows, folded somewhat steeply in the southern part of the island along axes having a northwest trend.

The Marble Bay Limestone is the formation containing the ore bodies of the Marble Bay, Cornell, Copper Queen and Little Billy Mines, all of which lie less than a mile east and southeast of Marble Bay. This formation occupies a belt from 1 to 2 miles wide and 8 miles long, extending across the northern end of the island in a northwesterly direction. It is not less than 1,500 feet thick. It is an exceedingly pure limestone low in magnesia, and is recrystallized throughout its extent into a medium fine-grained light gray marble. The bedding planes are almost obscured, but where distinguishable they indicate slight folding with gentle dips to the northeast. The relation of this formation to the Texada formation is not clearly shown at the contacts, owing to their irregular nature, but in general the lime-

stone appears to be intercalated in the volcanic rocks.[7] Some poorly preserved fossils found in this formation[8] indicate that it is of upper Triassic or lower Jurassic age.

Small areas of granodiorite and quartz-diorite of the Coast Range batholith occur at the Little Billy mine situated on the shore about 3,000 feet east of the Marble Bay, and at Priest Lake about 3,000 feet south of it. A body of granodiorite, quite similar to that at the Little Billy, was recently discovered in the seventeenth level of the Marble Bay mine itself. Three larger areas of the same rocks occur, two on the east coast, and one on the west coast of the island a considerable distance south of Marble Bay. The well-known magnetite deposits of Texada Island are located on the contact of the latter of these intrusives.

The intrusive rock at the Little Billy, at Priest Lake and in the bottom of the Marble Bay mine is a typically plutonic, medium coarse, light-gray rock consisting essentially of quartz, plagioclase about the composition of andesine, varying amounts of orthoclase, hornblende, augite and biotite. The three intrusions are so similar lithologically, and so closely situated to one another, that little doubt exists as to their being parts of the same large mass, which must extend for considerable distance below the surface. It seems to be equally certain that the ore found in the Marble Bay and nearby mines was formed by solutions emanating from the magma which formed these intrusions.

The stocks, dikes and irregular masses of diorite-gabbro and porphyrite are considered by McConnell to be late phases of the batholithic intrusion and were mapped as a separate formation. However, a close examination of these intrusions showed that while some of the dioritic phases are similar to the rocks of the Coast Range batholith, and in all probability belong to that group, yet the gabbro and diorite-porphyrites resemble more closely the volcanic rocks which overlie and underlie the lime-

[7] Clapp, C. H., Geol. Surv. Can., Memoir 13, pp. 61; memoir, 36; memoir 58, p. 105.

Dolmage, V., Geol. Surv. Can. Sum. Rep. 1918, Part B, pp. 32; 1919, Part B, pp. 15; 1920, Part B.

[8] McConnell, R. G., *op. cit.*, pp. 20.

stone. Also one of these stocks of diorite-gabbro on the seventeenth level was found to be cut by an apophysis of the granodiorite stock and, therefore, must be older. These facts seem to suggest that some, at least, of these stocks and dikes of basic rock represent feeders and off-shoots of the thick volcanic series which both overlie and underlie the Marble Bay limestone.

Some diorite-porphyrite dikes, however, are found cutting the quartz-diorite and also the magnetite ore bodies on the west shore of the island, thus proving that there were intrusions later than the quartz-diorite of the Coast Range batholith and also later than the mineral deposits which were formed after the consolidation of the batholithic rocks.

### FAULTING.

Faulting on a small scale has taken place both before and after the period of mineralization. That which took place after mineralization is of little account and resulted in only slight displacements. That which preceded mineralization was of greater extent and had an important bearing on the formation of the ore bodies. The most important fault observed is on the thirteenth level, where a 25-foot andesite dike striking in a northerly direction is dislocated and its northern block thrown about 120 feet to the east. In this fault zone there was discovered the "13–13" ore body, the largest and richest one so far encountered in this or any of the neighboring mines.

### ORE DEPOSITS.

The ore bodies of the Marble Bay mine have all proved to be moderately small but unusually rich. Their lengths vary from a few feet up to 220 and their widths from 10 feet up to 50 feet, while the vertical dimension is usually greater, in one instance reaching down 502 feet. They are very irregular in shape, widening, pinching and branching for no apparent cause, and frequently enclosing irregular masses of barren garnetite and limestone. The boundaries are usually clearly marked; in many

cases almost pure bornite abuts against almost pure marble, though in other instances the ore fades out somewhat gradually into garnetite.

One of the largest ore bodies so far found was encountered just below the 280-foot (fourth) level and extended down 502 feet, to a point 18 feet below the ninth level. Its maximum length was 220 feet and width about 15 feet. Below this level it divided into two branches; the smaller extending down to the seventh level, and the larger varying from 80 to 120 feet in length and up to 40 feet in thickness terminated at the ninth level. The tenth level was nearly barren, but another ore body was found 50 feet lower, which, though irregular, extended to the thirteenth level, where it diminished to a mere stringer. About 140 feet to the north on this level the fault mentioned above was encountered and on it was found the remarkable "13–13" ore-body. This was 210 feet long, had an average thickness of 40 feet and consisted of almost pure bornite with appreciable gold and silver. It extended above the tenth level for 60 feet; below it, it narrowed rapidly but continued in an irregular and broken manner down to the seventeenth level, where it came into contact with the granodiorite, which at this point is impregnated with chalcopyrite, silica and epidote.

## MINERALOGY.

The mode of occurrence, and in some cases the appearance of the minerals found in this deposit are described below.

*Metallic Minerals.*—The metallic minerals, named in the order of their relative abundance are: bornite, chalcopyrite, chalcocite, molybdenite, pyrite, pyrrhotite, magnetite, covellite, zincblende, argentite, tetrahedrite, galena, dyscrasite?, calaverite?, silver, gold, electrum.

*Bornite* greatly exceeds in amount all the other metallic minerals, and its preponderance is maintained on all the levels of the mine. It is closely associated with chalcopyrite, most of which is earlier than the bornite (Plate XII*a*), and other portions of it are decidedly later (Plate XII*b*). Much of the bornite seems to

have been deposited simultaneously with the chalcopyrite. The bornite is later than the pyrite which occurs with it, and is also later than the zincblende. The tetrahedrite, galena, argentite, dyscrasite, calaverite, gold, electrum and some of the chalcocite and native silver occur as blebs in the bornite, indicating neither earlier nor later deposition, but suggesting a deposition simultaneous with the bornite. (Plates XII*c*, XIII*c*.) All of the gangue minerals are earlier than the bornite excepting serpentine, laumontite, apophylite and calcite.

*Chalcopyrite* seems to be more plentiful on the lower than on the upper levels. It is the chief metallic mineral, and the only copper mineral, found in the mineralized portions of the granodiorite stock on the seventeenth level. In this ore it is disseminated in the feldspar and quartz in the manner shown in Plate XII*d*. It is also the only copper mineral in a class of ore composed of pyrrhotite, magnetite, and pyrite, which occurs at two places in the mine in close association with the gabbro-porphyrite stocks from which it is believed to have originated.

*Chalcocite* is found throughout the deposit in considerable amounts, and is almost, if not quite, as abundant in the lower as in the upper levels. It is always associated with bornite usually in a manner which does not indicate its paragenesis (Plate XII*c*). Other portions of it, however, are clearly seen to have been deposited later than the bornite, and these portions usually have a bluish color and are associated with native silver, covellite, and serpentine. It was never found in contact with chalcopyrite.

*Molybdenite* is more plentiful in the lower levels, but is present in all parts of the deposit. It is more commonly associated with chalcopyrite than with bornite. It was deposited after all the gangue minerals, except the zeolite, serpentine, and late calcite, and usually preceded the chalcopyrite. It occurs as small finely lamellated, tabular fragments (Plate XIII*b*).

*Pyrite* is an uncommon mineral in the deposit. Only a few small corroded crystals are found in the bornite ore. It is, however, fairly abundant in some of the porphyrite dikes, and in the small pyrrhotite ore bodies mentioned above, which are associated genetically with these basic dikes.

*Pyrrhotite* does not occur in the ordinary bornite ore bodies, and is present only in the small ore bodies just mentioned, of which two are known to occur in the mine, one on the upper levels and one on the fifteenth level.

*Magnetite* is found in the pyrrhotite ore bodies, and in the mineralized portions of the granodiorite on the seventeenth level, but is rarely found in the bornite ore bodies.

*Covellite* is present in small amounts in all parts of the ore bodies, the lower parts containing as much as the upper. It is associated only with bornite, in which it forms veinlets and small irregular replacements (Plate XII*a*). It was not observed replacing chalcocite, but some portions of the late chalcocite are much bluer than others, and this may be due to a mixing of the two sulphides. Covellite appears to have been the last mineral deposited in these ore-bodies.

*Zincblende* in minute quantities was observed in a large number of specimens, but was found to be more plentiful where chalcopyrite was abundant. It is a common mineral in the Loyal mine situated about three miles north of Marble Bay, where it is associated with galena and bornite. Zincblende is one of the earlier metallic minerals to have been deposited.

*Tetrahedrite* was observed in only one specimen, and there only in small amounts. It occurs as blebs in the bornite and chalcopyrite, and appears to have been deposited simultaneously with these minerals.

*Native Silver* was found in the ore of all levels and appears to be as plentiful on the lower as on the upper levels. Smelter returns of ore taken from depths of 460 feet to 960 feet show that the silver content increased from 3.1 oz. to the ton to 3.8 oz. per ton, and, as other silver minerals are extremely rare in the ore, it seems reasonable to assume that the native silver increased to this extent. The silver occurs closely associated with, and to some extent mixed with gold, both minerals forming irregularly shaped isolated masses in the bornite (Plate XIII*c*). It also occurs free from gold in the form of veinlets in chalcocite, and between chalcocite and serpentine (Plate XIII*a*). In the first

mode of occurrence its age relation is not clearly indicated, but it seems to have been deposited at the same time as the gold and bornite. In the second, it is clearly later than the chalcocite and serpentine.

*Gold* in a free state was observed in many polished sections of bornite ore, occurring in the manner just described (Plate XIII*c*). Smelter returns show that the gold values fluctuate considerably, but that there was no apparent decrease with depth, the average value being about .333 oz. per ton.

*Electrum* appears associated with the small masses of gold and silver mentioned above, and shown in Plate XIII*c*. They usually have bright yellow centers which consist apparently of pure gold, but these fade gradually until at the rims of such areas pure silver occurs. The intervening space is occupied by what seems to be a mixture or alloy of the two metals, which is probably the mineral electrum.

*Argentite* occurs in minute quantities in the bornite ores, where it forms small blebs apparently formed during the precipitation of the bornite.

*Galena* also occurs in very small amounts as rounded blebs in the bornite. It is abundant in the Loyal mine, where it is believed to be argentiferous.

*Dyscrasite*(?) is invariably present in the bornite from the lower levels as small round blebs of a creamy white, soft, metallic mineral. It reacts with etching reagents in a manner suggestive of dyscrasite. It occurs, however, in such small quantities, and in such fine specks, that it can not be conclusively identified.

*Calaverite*(?) occurs as a second creamy mineral, clearly distinguishable from the other minerals, in the bornite from the sixteenth level. It also is too finely divided and too scarce to be positively determined, though it reacts like calaverite. However, the presence of native tellurium in the Commodore, a similar neighboring deposit, makes the presence of a telluride seem not unlikely.

*Gangue Minerals.*—The gangue consists of the following minerals named in the order of their relative abundance: calcite,

grossularite, wollastonite, diopside, epidote, quartz, andradite, augite, serpentine, zoisite, sericite, albite, apophyllite, laumontite, thulite, vesuvianite.

*Calcite* in the form of small crystals constitutes the marble in which the ore bodies are formed. The marble is practically free from other materials, excepting a small amount of black opaque material, probably carbonaceous matter, which gives it a decidedly gray color. The ore minerals are frequently found enclosed in pure calcite with which they form sharp contacts. At the contacts of the ore with the marble, the gangue, and also the small dikes, there is invariably present a pure white zone, composed of calcite, usually a little coarse in grain and practically free from carbonaceous material. These white zones are persistent and conspicuous, varying in width from a fraction of an inch up to a foot or more. Such a zone is shown in Plate XIII*d* formed at the contact of bornite-wollastonite ore. The process by which the carbonaceous matter is removed is not understood. Calcite also occurs in small veinlets formed at a late stage in the mineralization.

*Grossularite* occurs in large fine-grained masses, composed of small equal sized anhedral crystals, and is usually closely associated with large amounts of diopside. This gangue seldom carries large quantities of the ore minerals.

*Wollastonite* is abundant in all parts of the deposit. Large masses occur in the limestone, usually free from other gangue minerals, excepting a small amount of diopside. Much of the best ore in the deposit is a fine mixture of wollastonite and bornite, as shown in Plate XIII*d*. The wollastonite forms in tufts and rosettes of white acicular crystals up to an inch in length, the bornite occupying small veinlets and intergranular spaces.

*Diopside* is found in considerable quantities in many parts of the deposit, and is usually associated with grossularite. It occurs as small crystals scattered through the garnet, and also in large aggregates of small rounded crystals. In the latter form it is dull grayish green, but some of the larger crystals in the

garnet are of a bright green color and highly lustrous. Under the microscope it is colorless or faintly green with a slight pleochroism, an extinction angle of about 38°, and the intermediate ray has a refractive index of about 1.68. These properties indicate a pyroxene low in iron.

*Epidote* is nowhere present in large amounts. It occurs as small veinlets in the altered granodiorite, and also in a small aplite dike. It also forms fine-grained mixtures with quartz, which usually contain considerable chalcopyrite. In a small aplite dike on the fourteenth level a colorless variety was found scattered evenly among the grains of quartz and feldspar.

*Quartz* is much less plentiful in this deposit than in most deposits of this type. The silicification of the limestone which is such a common feature in contact metamorphic deposits is not known to occur in this one. Quartz is plentiful in the altered granodiorite and scattered grains are found occasionally in the chalcopyrite ore.

*Andradite* garnet, a greenish black variety, occurs in coarse-grained aggregates of dodecahedrons, and has a refractive index exceeding 1.78. It is not usually mixed with other gangue minerals but is frequently associated with considerable quantities of bornite.

*Augite* was observed only as small veinlets cutting basic dikes of black fine-grained hornblende-labradorite rock on the thirteenth level. The veinlets, which contain nothing but augite, vary in width up to one-tenth of an inch and are bordered on either side by light-colored bands up to one-half inch in width, in which the black hornblende of the host rock is replaced by a pale greenish augite similar to that occupying the veinlets.

*Serpentine* occurs plentifully in the ore of this deposit. On the fourteenth level bands of serpentine from two to twelve inches in width were found in the limestone. It is not closely associated with other gangue minerals except small amounts of diopside. It does, however, contain considerable amounts of ore minerals, such as bornite, chalcopyrite, chalcocite and native silver. The bornite and chalcopyrite occur in the serpentine as

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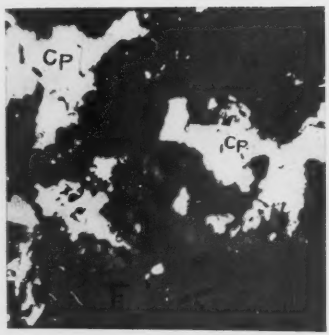
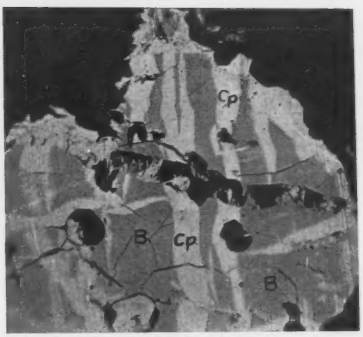



*a*

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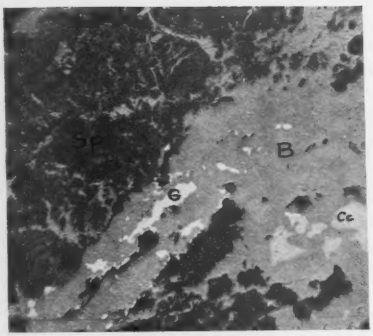
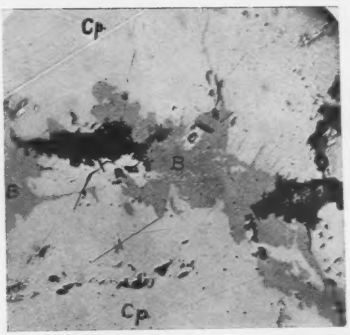



*c*




*d*

*a*. Covellite (Co) replacing bornite (B) and chalcopyrite (Cp), × 475.
*b*. Chalcopyrite (Cp) replacing bornite (B), both fractured and repla[illegible] by Serpentine (sp.), × 350.
*c*. Bornite (B) replaced in peculiar manner by serpentine (sp.). [illegible] chalcocite. G = gold and silver, × 360.
*d*. Chalcopyrite (Cp) replacing granodiorite. F = feldspar, × 360.

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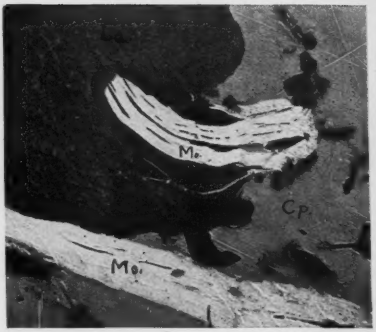
*a*

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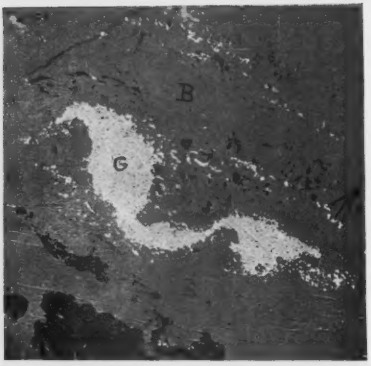



*c*

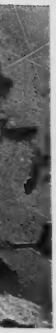
*d*

*a*. Native silver (s) replacing chalcocite (Cc) and serpentine (sp) in bornite (B), × 700.

*b*. Molybdenite (Mo) in chalcopyrite (cp) and calcite (Ca), × 280.

*c*. Gold (G), silver (s), chalcocite (Cc), and serpentine (sp) in bornite (B), × 280.

*d*. Bleached band in grey marble at contacts of marble and ore. Above is bornite-wollastonite ore; below is marble. ½ natural size.



small rounded grains about one-sixteenth of an inch in size, which are clearly residual. The chalcocite and native silver are, for the most part, later than the serpentine.

In hand specimens the serpentine is either a dark green color or honey yellow. It is homogeneous in appearance, has a flinty fracture, a greasy luster, and is noticeably translucent. Under the microscope two varieties were observed, the fibrous variety, asbestos, and the platy variety, antigorite. This parallel arrangement is, however, not common, the greater portion has a platy structure and therefore probably belongs to the antigorite variety.

*Zoisite* was found in small amounts in the quartz-epidote gangue and also in the aplite dike occurring on the fourteenth level.

*Sericite* occurs as an alteration product of the feldspar in the aplite dike and of the feldspars in the altered granodiorite.

*Albite* is probably the feldspar contained in the aplite dike, but it is so completely sericitized that its twinning and extinction angles could not be observed. It is either albite or orthoclase, probably the former.

*Apophyllite* was found in small quantities on the fourteenth level and also on some of the higher levels. That on the fourteenth level occupies small veinlets about one-tenth inch in width, cutting the quartz-zoisite gangue and the wollastonite-bornite ore. In the upper levels it occurs both as veins and as incrustations lining small cavities. These incrustations are composed of perfectly developed cubes about one-eighth of an inch in size.

*Laumontite* also occurs in small veinlets cutting quartz, zoisite, wollastonite, chalcopyrite, and bornite. The veinlets appear to be among the latest to have been formed in the ore. Some of these veinlets contain a small amount of calcite associated with the laumontite.

*Thulite* was observed with young minute crystals intergrown with zoisite and epidote in small pink areas in the quartz-epidote-zoisite gangue. The crystals have the form of minute blades which extinguish parallel to the direction of elongation and possess a marked pleochroism changing from bright yellow to a

deep pink. The index of refraction of the pink ray was found to be about equal to 1.70.

*Vesuvianite* was not observed by the writer, but it is said by Mr. McConnell and others to have been found in the Marble Bay Mine.

### RELATION OF THE MINERALS TO EACH OTHER.

The structures seen in the hand specimens and polished sections indicate clearly that the gangue minerals, garnet, pyroxene, wollastonite, quartz, epidote, zoisite, and thulite were formed previously to all of the metallic minerals, excepting, perhaps, the pyrite, which may have been deposited at the same time. It is equally clear that serpentine, calcite, laumontite, and apophyllite were deposited later than the metallic minerals, except some of the native silver, some of the chalcocite, and the covellite. This divides the mineralization into four periods: first, the garnet-wollastonite-pyroxene period; second, the chalcopyrite-bornite period; third, the calcite-zeolite period; and fourth, the serpentine-native silver-covellite period.

In the first period the limestone was replaced by large masses of grossularite, diopside, quartz, epidote, zoisite, thulite, augite, and andradite. There is nothing to indicate the exact order in which these minerals were deposited, but it seems likely that the diopside and grossularite were deposited together, and that the quartz, zoisite, epidote and thulite were formed as a group. It is probable that all of these minerals were formed more or less simultaneously. In a contact metamorphic deposit at Matchuala, Mexico, Spurr[9] found almost exactly the same set of gangue minerals, and observed that the non-ferrous minerals, such as wollastonite, diopside, and grossularite, preceded the iron minerals, hedenbergite, andradite, and actinolite. This sequence is not indicated in the structures observed in the Marble Bay mine, but this may be due to the comparatively small amount of the iron-bearing silicates present, the amount of augite and andra-

[9] Spurr, E. J., "Study of a Contact Metamorphic Ore Deposit, ECON. GEOL., Vol. V., 1912, pp. 444.

dite being almost insignificant in comparison with the grossularite, diopside, and wollastonite.

The second period, consisting in the deposition of most of the metallic minerals, followed immediately, and to some extent overlapped the preceding period. The first minerals to be deposited were pyrite and magnetite, in minute quantities only. These were followed by zincblende, molybdenite, and chalcopyrite in the order named. Then bornite and its associated minerals, chalcocite, galena, argentite, gold, silver, electrum, dyscrasite, and calaverite were all deposited about the same time. Following this the ore suffered considerable crushing and fracturing, after which chalcopyrite was deposited in the fractures of the bornite.

Then followed a period of intense crushing during which the chalcopyrite and bornite with its associated minerals were strongly sheared. In the openings caused by this movement were deposited apophyllite, laumontite, and calcite.

The fourth period was characterized by the deposition of serpentine, considerable chalcocite, native silver and a small amount of covellite. The silver is certainly later than much of the chalcocite, and usually occupies veinlets formed between the chalcocite and serpentine. The covellite is known to be later than the calcite veinlets, which were formed at the end of the third period, and seems to be the last mineral to have been deposited in the ore. It most often occurs at the contacts of the calcite veinlets with chalcopyrite, chalcocite, and especially bornite.

### ORIGIN OF THE ORE.

The fact that the ore-bodies of the Marble Bay mine, when followed down through the limestone, lead directly to a stock of granodiorite, which is itself considerably mineralized; also, that at the Little Billy mine, one-third of a mile to the east, similar ore bodies are formed in the same limestone at the contact of an intrusion of almost identical granodiorite of Coast Batholith age; and that scores of copper deposits in the Coast section of British Columbia are known to have originated from the intru-

sion of this age, all tend to establish the belief that the ore in the Marble Bay mine originated in the granodiorite stock recently discovered in the seventeenth level.

It is also highly probable that the ore of the Cornell and Copper Queen mines originated in intrusions of the same rock, which have not yet been reached in the workings.

The ore solutions which formed these deposits were evidently of an unusual composition. The great preponderance of non-ferrous or low ferrous silicates, such as wollastonite, grossularite, diopside, and colorless epidote, over the ferrous-minerals andradite and augite, and the absence of such common ferrous-minerals as the amphiboles, indicate that these solutions were exceedingly low in iron. Likewise the great preponderance of bornite over chalcopyrite, the almost entire absence of pyrite, pyrrhotite, and magnetite in the average ore, and the presence of large amounts of chalcocite which seem to be of primary origin, indicate solutions low in iron and high in copper.

It is also worthy of note that there are no arsenic minerals and, except for a very small amount of tetrahedrite and some doubtful dyscrasite, no antimony minerals in this deposit.

The solutions which formed this deposit afford an interesting comparison with those which came apparently from the same magma, but formed the huge deposits of magnetite situated four miles distant in the same formations. In the magnetite deposits one finds, besides large quantities of magnetite, much pyrrhotite, hematite, pyrite, and some chalcopyrite, and among the gangue minerals andradite, dark green epidote, green actinolite, siderite, and pyroxene, all of which point to a high concentration of iron in those solutions. However, the minerals, magnetite, hematite, and pyrrhotite also indicate higher temperature conditions, and suggest that these solutions were emitted from the magma at an earlier period than the solutions which formed the Marble Bay and neighboring deposits. From this it would appear that the concentration of the rarer metals in these mineralizing solutions is a progressive process which keeps pace with the crystallization

and probably also with the differentiation of the magma from which they come.

In the score or more of contact-metamorphic deposits which occur in Vancouver and its adjacent islands, and which are formed at the contacts of the limestones of the Vancouver Group with the intrusions of the Coast Range batholith, one finds every gradation from the magnetite deposits, composed entirely of minerals high in iron, to copper-silver deposits like the Marble Bay, which contain an exceedingly small amount of iron in gangue as well as ore minerals. The most common type is one of intermediate composition, in which chalcopyrite predominates and is the only copper mineral present. Bornite is found only in deposits of high copper content. Chalcocite is found only with the bornite.

Whereas most of the minerals may with certainty be attributed to the action of solutions emanating from the underlying granodiorite, there are some which seem to have been deposited by descending vadose waters, viz., chalcocite, native silver, covellite and serpentine.

Of these minerals the most abundant is chalcocite. This is the most common copper mineral in enriched deposits, and is particularly abundant in those containing bornite. It is well known that bornite is susceptible to alteration into chalcocite. This, and the fact that the two minerals bornite and chalcocite are almost invariably associated with one another, have been important factors in leading some investigators to the conclusion that chalcocite is invariably a secondary mineral attributable to the action of surface solutions. However, the mineral has been found in places where the possibility of its having been acted upon by surface solutions is practically precluded, and it is the writer's opinion that its association with bornite may be more reasonably explained than by always attributing it to the action of oxidized solutions.

When chalcocite occurs in deposits where the bulk of the evidence favors a primary origin it is, so far as the writer can ascertain, always associated with bornite. It was pointed out

above that in the copper deposits of Vancouver Island and vicinity chalcocite is present in all those which contain bornite but is absent in those which do not contain bornite. As all of these deposits have had practically the same history, it would be unreasonable to argue that all the bornite deposits had been enriched and all the others had not. In deposits, however, which are known to have been enriched, chalcocite is abundant, but is as plentifully associated with pyrite and chalcopyrite as with bornite.

These two considerations (1) that in primary deposits chalcocite is present only if bornite is also present, and (2) that in enriched deposits chalcocite is present whether bornite is or not, may be explained by the following hypothesis: Chalcocite will be precipitated by primary solutions providing the ratio of the concentration of copper to that of iron in such solutions is relatively high. Such solutions would naturally precipitate bornite in preference to chalcopyrite, the latter having a higher iron content. It is also clear that solutions incapable of precipitating bornite would be less able to precipitate chalcocite, so that in primary deposits containing no bornite chalcocite should not be expected, and, so far as the writer is aware, is not found. In the case of enriched deposits the secondary minerals are precipitated by entirely different solutions from those which formed the primary minerals and consequently chalcocite, the characteristic secondary mineral, might be expected to be, and usually is, associated as abundantly with pyrite and chalcopyrite as with bornite. If this hypothesis is correct chalcocite associated with pyrite and chalcopyrite in the absence of bornite would be strong evidence of secondary enrichment, but if bornite were also present the chalcocite might as likely be primary as secondary.

However, in the Marble Bay deposit, though much of the chalcocite may be primary, there are reasons for believing that some of it may be secondary. Some of the chalcocite was deposited before the serpentine and some of it after. Another reason is that the earlier chalcocite shows signs of crushing while the later does not. And a third reason is that the later chalcocite

is associated with covellite and native silver, two minerals which are characteristic of enriched deposits.

Native silver is an exceedingly common secondary mineral and occurs plentifully on all levels of the mine. Much of it (Plate XIII*a*) is later than both the serpentine and the chalcocite and shows no sign of having been crushed.

Covellite is almost as persistently present in enriched deposits as the above-mentioned minerals, and it, too, is formed in many parts of the mine, though in small amounts. It is usually found on the margins of the late calcite veins, which indicates that it was precipitated at a late stage in the history of the deposit.

Serpentine is also frequently formed in deposits of this class by the hydration of pyroxene by surface waters. Such a case is cited in the Clifton-Morenci district, Arizona, by Lindgren.[10]

Now the presence of any one of these minerals alone might not prove the action of surface solutions; but the fact that all four of them are present in considerable quantities, and that they were introduced after the bulk of the ore minerals had been deposited and had suffered considerable fracturing, is strong evidence that these ores have been enriched in this way. The extremely permeable nature of the fractured limestone and such cleavable gangue minerals as wollastonite would greatly facilitate circulation of solutions and hence the enrichment of the ore.

The evidence opposing this theory also seems formidable. The position occupied by these ores, a great distance below sea level, would make the circulation of surface waters seem almost impossible. The uniform distribution of the minerals over a vertical range of 1,500 feet, with no indication whatever of rich zones related to the surface, is also opposed to such a theory. There is no indication of the oxidized zone that is almost invariably present in enriched ore deposits. And it is known that the present surface has been deeply cut away by the action of ice in the glacial period.

All these objections, however, would disappear if it could be

[10] "The Copper Deposits of the Clifton-Morence district, Arizona," U. S. Geol. Surv. Prof. Paper No. 43, pp. 110.

shown that the enrichment had taken place during a preglacial period when the deposits were above sea level, and that, after enrichment and before the glacial period, the deposits had been depressed to their present submarine position. Such events would have exposed the deposit to the action of circulating surface waters, and then, by their depression below sea level would have protected the enriched ore from the action of the Pleistocene glaciation. In view of the geological history of the region this would seem possible and not unlikely. The deposits were formed in late Jurassic time. Not long afterwards they were depressed below sea level and a thick series of Cretaceous sediments were deposited on them. At the close of the Cretaceous, probably during the post-Laramie dynamic revolution, the region was elevated to a point much higher than it now occupies. During the early Tertiary it was subjected to a long period of erosion which removed the Cretaceous sediments and probably cut down into the Texada formation. After this long period of erosion had reduced the land surface almost to a peneplain, it was again elevated and the present land forms carved. Just prior to the glacial period, however, the region was again depressed to form the drowned shore-line which now exists.[11]

If the ores in the Marble Bay deposit had been enriched just before this last depression the results would correspond with the conditions now found. The ice of the Glacial Period would have removed the oxidized zone and probably some of the enriched zone, but the latter, being mostly below sea level, would have been protected from the ice and preserved in its present form.

Three alternatives, therefore, present themselves; either all the chalcocite, native silver, covellite and serpentine are primary, or else surface enriching solutions have circulated through the ore in its present submarine position, or else the deposits were enriched and later depressed to their present position during a preglacial period. To the writer the latter seems most probable.

GEOLOGICAL SURVEY OF CANADA,
OTTAWA, CANADA.

[11] Dawson, Geo. M., *Trans. Royal Society*, Canada, Vol. VIII, 1890, Sect. IV, pp. 17. Clapp, C. H., Geol. Surv., Canada, Memoir 13, pp. 18.

# GEOLOGY OF GYPSUM AND ANHYDRITE.

D. H. NEWLAND.

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## INTRODUCTION.

Field work on the calcium sulphate materials, as a rule, has been of rather cursory character. This stands as no reflection on the methods of investigation which necessarily have had to be adapted to conditions. In America gypsum mining is a relatively new industry insofar as stable and large-scale operations are concerned, and the available field for geological study in years past has been limited for the most part to the superficial areas—with natural exposures few and scattered by reason of the soluble nature of the minerals—wherein observations may have been supplemented to some extent by well borings that were made more often than not for purposes other than the location of gypsum deposits.

With the substantial growth of activity in the last few years, particularly in the eastern districts of the United States and Canada, the situation is rapidly changing. The more available supplies in some places have been worked to the limit, so that exploration has had to be pushed into new territory and to increased depths. Observations are now practicable where formerly there was little recourse but to surmise from data of variable accuracy and degree of application. Furthermore, the mining companies have come to realize the value of the core drill and other approved methods of guidance in the planning of their operations.

From a somewhat extensive acquaintance with the progress of mining in leading gypsum districts during late years, the writer has come to feel the need for revision of current information, or at least a more definite statement in several particulars about which there is a good deal of obscurity prevailing and which

have a bearing on the geological relationship of both gypsum and anhydrite. Such a revision, judging from published works that have been consulted, is warranted by the apparent divergence between individual interpretations and as well by the importance of the economic features concerned.

It is the purpose of the present article to consider some of the data available for use in this connection, such as have come under personal observation or to which the writer has had ready access, with a view to bringing them to notice and to elicit information from others who have had experience in this field.

Perhaps the most salient feature in connection with the occurrence of calcium sulphate minerals that is brought out in the course of the article is the geological importance of anhydrite and its predominance over gypsum as a rock-forming mineral. If the evidence has not been misinterpreted gypsum is more or less an incidental development, closely restricted in distribution, whereas anhydrite under prevailing geological conditions is the persistent and stable compound. The presence of the latter is to be taken as probable in every deposit that extends to any depth from the surface, that is, below two or three hundred feet. In some instances only a part of the rock may be in anhydrous form, consisting of a fine intergrowth of the two minerals that will require the microscope or chemical analysis to show its complex character, or there may be aggregates or masses of anhydrite included in gypsum; in either case the state of admixture often escapes attention and the material passes as gypsum. In most of the older districts miners have become familiar with the presence of the harder denser compound, but seldom recognize it by its mineral name, calling it "hard" gypsum or occasionally limestone.

Until the research of A. F. Rogers[1] a few years since, anhydrite was little known in this country, having been listed in only a few places. He was able to enumerate about 60 localities, but his list could now be extended by the inclusion of many

[1] "Notes on the Occurrence of Anhydrite in the United States," *School of Mines Quarterly*, vol. 36, No. 2, 1915, pp. 123–142.

districts and mines where exploration has progressed beyond the outcrop zone.

Whether gypsum or anhydrite predominates at any locality depends upon physical conditions, and it is therefore essential to examine the properties of the minerals themselves in their relation to environment.

## PHYSICAL DATA.

*Precipitation.*—If a solution of sodium chloride and calcium sulphate be evaporated, the calcium salt will precipitate first in the form of gypsum, but as concentration progresses to the point of saturation for sodium chloride the precipitate changes to anhydrite when the temperature reaches 30° C. The rest of the sulphate comes down in anhydrous form. With sea water the change to anhydrite takes place at 25° (Van't Hoff and Weigert's experiments). Inasmuch as a temperature of 25° C. more than likely would be reached by surface waters in arid climates during seasons of rapid evaporation, the original precipitates for marine sulphate deposits like those of the Salina formation, were probably anhydrite or layers of anhydrite and gypsum with the former predominating. There seems little chance that they consisted primarily of gypsum alone.

*Temperature.*—Gypsum, it is well known, loses its water under heat. The temperature required for dehydration is a function of pressure and time. Le Chatelier found the temperature for experimental conditions to be 163° C. at atmospheric pressure. On the other hand Shenstone and Cundall accomplished the dehydration at 70° in a current of dry air. It is said the water begins to go off at as low as 15° C. in dry atmosphere, and chemists are familiar with the fact that there is likelihood of water loss when grinding gypsum in a mortar. The significance of the time and pressure factors have not been satisfactorily investigated within the writer's knowledge; they have the chief interest from a geological standpoint since their influence is fairly certain to have been more important in the process of dehydration of buried beds of gypsum than heat on the basis

of the gradient of earth temperatures at depths to be inferred in such case.

*Pressure.*—The change from gypsum to anhydrite involves a shrinkage in volume of 35–40 per cent. The conditions presented by horizontal layers or beds under permanent load of overlying sediments, such as obtain in most gypsum districts, are conducive to the existence of the mineral with the more compact molecular structure, that is, anhydrite. This does not mean, of course, that gypsum is necessarily unstable under load, but there is a critical depth at which under normal conditions transformation takes place. That such change has occurred is a matter of inference rather than of direct observation, as there are no places where it can be proved as operative at present or in the past. Pseudomorphs of anhydrite after gypsum are rare, if known at all in such surroundings as to indicate the agency of pressure in their production, and it is hardly to be expected that they should occur.

At atmospheric pressure and temperatures gypsum is the stable and anhydrite the unstable form. This fact is amply proved by the prevalence of gypsum in the outcrop zone, by the deposition of gypsum by ground waters and as efflorescent growths on soils (*e.g.,* gypsite beds) and by the microscopic relations of the two minerals in mixed rock from various places where the transition zones lies within the reach of observation. The change anhydrite → gypsum is noted by Rogers for several localities in the paper already cited. It has been frequently observed by the writer in samples taken from drill cores and mines in the older mining districts.

The pressure required to maintain anhydrite in equilibrum with conditions represented by burial under sedimentary cover should be susceptible of determination by direct evidence, and certain data are available that bear directly on this point and that indicate a very moderate figure. In view of the amount of exploration that has been performed for oil, gas and salt, in which gypsum or anhydrite beds have been encountered, the matter would seem easy of solution on the basis of the data, but it is

necessary to exercise much care in the employment of such evidence. It is apparent after brief survey of conditions that the usual well record is unreliable in failing to discriminate carefully between the two minerals.

The gypsum districts of western New York supply the most reliable information that has come to the writer's notice. The deposits have the form of thin seams which slope very gradually (1 in 100) to the south of their line of outcrop. The surface is little broken for a mile or so, but then rises sharply as the beds of the overlying Onondaga formation (cherty limestone) appear, with an east-west outcrop parallel with that of the Salina beds which hold the gypsum. There has been no material change of surface features since the withdrawal of the Pleistocene ice-sheet. Conditions with regard to the sulphates, thus, may be considered to be fairly adjusted. The gypsum may be followed underground from the outcrop edge along the dip with gradually increasing cover as the higher beds of the Salina appear. To the south of the mine workings the ground has been core-drilled in places to the top of the Onondaga ledge where the deposits are covered by 250 feet of sediments. Anhydrite begins to show in the rock at 100–125 feet depth and its proportions increase more or less steadily in ratio with increasing cover. The critical depth seems to be around 250–300 feet, below which the mineral, except as cavity and vein fillings, is in the form of anhydrite.

Similar conditions are known to occur in the Salina gypsum of southern Ontario. The deposits there are a continuation of the western New York series.

Michigan supplies many well tests that record the presence of calcium sulphate, but it is evident that they have to be used cautiously as criteria for the distribution of gypsum. Grimsley[2] has made the most exhaustive study of conditions in that state, as a result of which he concludes that all deposits below about 500 feet are in the form of anhydrite, the identification being

[2] "The Gypsum of Michigan and the Plaster Industry," Geol. Surv. Mich., p. 84. Lansing, 1904.

at fault whenever gypsum is reported as having been found below that depth. That such is the likely condition is indicated by the appearance of anhydrite in some of the deeper workings at Grand Rapids.

The deepest gypsum mine is at Centerville, Iowa, where the shaft reaches a 13-ft. bed at 533 feet vertical depth. The deposit is reported to contain anhydrite in quantity,[3] and the presence of gypsum may be the result of some environmental circumstance not revealed in the published descriptions. Further work seems to be needed to develop the real conditions.

In the salt mounds of the Gulf coast gypsum is reported to occur at depths of 1,000 feet and more. There is reason to question the accuracy of the records, which are based on results of oil-well exploration, as is remarked by R. W. Stone.[4] In one instance at least, that of the well put down 3 miles west of Sulphur City, Calcasieu Parish, it would appear that the substance is actually gypsum, for Harris[5] describes the material as "pure gypsum, dense, granular, and coarsely crystalline, grayish or white." The bed is reported as 540 feet thick, extending between the depths of 690 and 1,230 feet from the surface. There is little question in regard to the migratory nature of the sulphate minerals in the mounds, and the peculiar structures involved in the occurrences may have something to do with the existence of the hydrated mineral at such depths. It is to be noted that in the Prussian potash deposits, which afford the most authentic data on the occurrence of the sulphates in the deeper zone, the mineral is prevailingly anhydrite. The gypsum of Louisiana seems to constitute a marked exception to the ordinary condition, which may be thought of as indicating some interference with the normal pressure effects. It is to be recognized, of course, that faulting, folding, or other departure from the condition of flat unbroken seams, involve special problems

[3] George F. Kay, in "Gypsum Deposits of the United States," Bull. 697, U. S. Geol. Surv., pp. 107–110, 1920.

[4] "Gypsum Deposits of the United States," Bull. 697, U. S. Geol. Surv., p. 121, 1920.

[5] "Oil and Gas in Louisiana," Bull. 429, U. S. Geol. Surv., p. 100, 1910.

to be treated in the light of the local evidence and not from a general standpoint. Occurrences of gypsum in veins or cavities, also, do not enter into consideration as bearing on the distribution of the mineral under load, as will be readily apparent.

From the information in hand it would appear that the stable calcium sulphate mineral under compression represented by a load of more than a few hundred feet of sediments is anhydrite. In the Salina formation the required cover is around 250–300 feet, and in Michigan probably under 500 feet. The evidence elsewhere is not conclusive enough to admit any broad deduction to be made on its basis, but it seems quite likely that after allowance for local variations induced by structural differences, etc., the distribution of gypsum and anhydrite will conform more or less closely to the relations indicated for the better known examples.

Under shallow cover anhydrite undergoes alteration to gypsum and expands in the process some 50 or 60 per cent. against the counter effects of pressure. This amounts to about 120 pounds to the square inch for each 100 feet of depth. The change may be observed in progress in most districts where exploration has extended below the outcrop zone.

It is to be remarked that the examples so far cited are of the class in which the change proceeds from anhydrite to gypsum, or is a katamorphic reaction. Illustrations of the opposite change by which anhydrite results from gypsum as the effect of augmented pressure by burial have not come to attention, and in the nature of the case would be rarely recognized in the field. That conditions must have made for such reaction in the past, however, seems very certain. It has already been indicated that some of the sulphate deposited by surface waters may have been in the form of gypsum; the burial of such bodies under many hundreds and even thousands of feet, that is to be inferred for nearly all of the older districts geologically, supplies the physical environment necessary to effect their conversion to anhydrite.

A corollary of this statement is that once anhydrite is encountered in abundance in a series of deposits, it is likely to per-

sist and constitute the permanent sulphate for any increase of cover.

### ZONAL DISTRIBUTION.

The arrangement of the calcium sulphate minerals may be referred to as zonal—characterized by an upper gypsum zone of relatively shallow depth and a continuing anhydrite zone below. The lower limit for anhydrite is indefinite, or rather it reaches depths where the conditions make for a general reconstruction of sediments through breaking down of the chemical affinities. The contact of the two zones is not always, or perhaps even commonly, a plane, but is marked by gradation through a vertical range that is comparable in places to the gypsum zone in extent. The overlap may be taken as indicating that both gypsum and anhydrite are in equilibrium within a certain range of depth or so nearly so that alteration proceeds with extreme slowness.

Such relationship conforms with geological principles, and there would be nothing particularly novel in its presentation here, except for the view as to the limited area occupied by the hydrous sulphate. This feature does not seem to have been noted or emphasized hitherto, in descriptions of gypsum deposits, although of the greatest consequence from an economic and geological standpoint. Conditions are encountered in the field which call for special consideration, but, these aside, the principle has broad application to deposits of rock gypsum that possess industrial importance.

Deviations from the rule are attributable in many instances to the influence of ground waters or erosion. Gypsum is the most soluble of the rock materials that ordinarily appear at the surface in regions of moderate to heavy rainfall. Waters in gypsum mines are always charged with sulphates, so much so in many mines as to give trouble in drainage or in use of the waters for boiler purposes. An effect of solution is to diminish the volume of gypsum at the outcrop. If long continued the more soluble mineral may be removed so as to leave the anhydrite zone alone in evidence. The Nova Scotian deposits supply many

illustrations of the rapidity with which gypsum may be carried away by surface waters. On steep slopes or cliffs the material is likely to be anhydrite even at the surface, as the wash removes the gypsum as rapidly as formed. The best conditions for the occurrence of soft thoroughly hydrated rock there are supplied by flats or gently sloping ground on which lies a protecting cover of soil or clay.

In western New York, where the beds are thin as a rule, the gypsum rarely appears at the surface, but the place of outcrop is marked by a depressed area produced by solution of the beds and caving of the overlying strata. The undiminished gypsum deposit is first found at rock depths of 20–40 feet. From the highly sulphated waters that issue from the outcrop it is surmised that the regression of the outer edge of the bodies is still in progress.

Differential erosion, faulting, or any other interference with the normal distribution of load will result, of course, in deviations from the indicated arrangement. The effects of faulting are not exhibited in the deposits of the eastern and central states, with possibly the exception of those of Virginia of which the writer has no personal knowledge. They are shown in a large way in Cape Breton where block-faults outline the areas and have produced vertical cliffs that as already stated are usually made up of anhydrite and that may extend well above the position of the hydrated rock. Between erosion and faulting the arrangement of the minerals in both vertical and horizontal directions has become very complicated, as manifested in the successive alternations of gypsum and anhydrite from the surface downward, the abrupt termination of the deposits in a horizontal plane, and the large-scale inclusions of one material in the other. The great bodies of sulphate that measure 100 feet or more across the planes of maximum extension find no counterpart in most mining districts of this country.

## GEOLOGICAL SIGNIFICANCE OF GYPSUM.

The foregoing statements in regard to the distribution of deposits underground and the superficial extent of gypsum, based on conditions as prevailing in the greater number, perhaps, of commercial deposits, involve the conclusion that the mineral is of recent derivation, restricted to an environment essentially of the present day. In glaciated districts the hydration is determined or influenced by the topography developed during and since the Pleistocene, for the earlier formed soft rock in the outcrop zone would hardly have resisted erosion by the moving ice-sheet wherever it worked with its usual efficiency. Elsewhere the relations should conform with the later stages of topographic adjustment, and the depth of the gypsum zone in a way will give an idea of the stability of the present surface features.

In other words gypsum is a weathering product, comparable in its occurrence to the habits of limonite as alteration product of the iron ores, with the reservation that anhydrite, the parent mineral of gypsum, is less resistant to weather than is magnetite or hematite.

As to the rapidity with which anhydrite changes to the dihydrate, few observations seem to have been recorded. The rate is influenced beyond doubt by temperature, moisture, and other conditions which make for solution of the material, for it is not a question of the simple absorption of the proportions of water necessary, but there is an actual solution of the anhydrite molecule by molecule and the reprecipitation of the calcium sulphate in hydrated condition. In the process some of the calcium sulphate may not be reprecipitated in place, but may migrate in solution toward the surface and there be deposited or wasted in the run-off. That anhydrite does change fairly rapidly when exposed to the weather has been observed in samples that had lain on a dump in the open for two years. The surfaces of the rock had accumulated in that time a coating of gypsum sufficient to be noticeable at a distance owing to its lighter color in contrast

with the gray ground of the anhydrite. Below the surface, where the anhydrite is in constant contact with water—most gypsum mines are wet—the change may be supposed to progress more rapidly, so as to respond to the modifications of environment incident to the forces at work producing changes in the surface relief.

In view of the relations as herein described it appears rather difficult to account for the presence of gypsum in the Texas and Louisiana salt mounds on the theory that it has crystallized in place from solution under rock pressure corresponding to the indicated depths. Its agency in the production of the domes by the lifting forces exerted during crystallization would seem equally improbable. Such gypsum as may occur is more likely an after-effect of the uparching of the limestones through another process, the mineral then coming to deposition by solutions set in motion by differential pressure. The key to the problem seems to lie, therefore, in the direction of tectonic adjustment, which has already been suggested as one explanation; but there is still too much uncertainty as to the real conditions surrounding the distribution of the sulphates to give decisive value to any deduction at this time.

With a volume increase of 50–60 per cent. from hydration, the weathering of thick beds of anhydrite under sedimentary load would appear to imply changes of surface relief such as should be readily noticeable. Direct evidence of such effects is scant and inconclusive. In New York and Ohio the position of the gypsum in certain areas is marked by the elevation of the surface above the general level, but so far as the conditions are known the alternative is admissible that the relief has resulted from settlement of the adjacent ground through removal of the sulphates. Much of the expansion, in any case, would have been taken up by the openings within the strata—joints and bedding planes—as the cover is mainly limestone that shows solution effects.

As a rock-forming material gypsum must take a very subordinate place. Surface indications are apt to give the impression

of a wider occurrence than it actually has, either superficially or in depth. Most of the consolidated calcium sulphate occupies the zone below that where hydration is in progress and where gypsum probably is unstable.

It may be added that outcrops by themselves have no great value as criteria for the consideration of geological principles applicable to the structure and origin of gypsum deposits, although frequently used in that connection, or for the estimation of resources of a particular locality or district. Hence, comes the need for study of conditions as presented by the later developments in the mining field, and it is hoped that the interest of those having opportunity for such observation may be enlisted in the effort to clear away present obscurity by supplying concrete results of their findings.

ALBANY, N. Y.

# A PRACTICAL METHOD FOR DETERMINING DIP AND STRIKE.

CHESTER R. LONGWELL AND EVERETT O. WATERS.

Within the last few years a number of short discussions on dip determinations have appeared in this Journal. None of these articles have considered the problem of finding the dip of beds from two observed components, and it has appeared to the writers of the present article that such a discussion may be desirable. In field work the case illustrated in Fig. 26 is sometimes encountered. Sections are exposed in the sides of two tributary

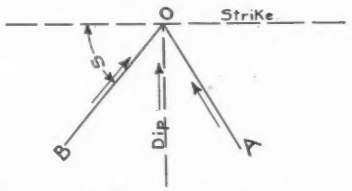


FIG. 26. Sketch to show factors involved in dip problems.

valleys. In each section the dip component is small, but uniform and measurable. It is possible, of course, by using plane table and alidade, to determine on a given bed the relative elevations and locations of three points, and with these data the method of dip and strike computation set forth by Roe[1] may be employed. However, the means for accurate location of the points may be lacking, and another method for determining the attitude of the beds may then be desirable. If the amount and direction of each component can be measured, the strike and dip may be computed in the following manner:

*AO* and *BO*, Fig. 26, are projections of the vertical planes in which the dip components are measured. *AOB* is the angle be-

[1] Roe, J. W., *Trans. Inst. Min. Eng.*, vol. 41, pp. 512–514, 1911.

tween the planes, and $S$ is the angle between the line of strike and $BO$. Let $D$ represent the angle of dip, $a$ the slope (that is, the tangent of the angle of inclination) in the plane $AO$, $b$ the slope in the plane $BO$. Then it can be shown that

$$\tan S = \frac{\sin \overline{AOB}}{\frac{a}{b} - \cos \overline{AOB}},$$

$$\tan D = \frac{b}{\sin S}.$$

If $\overline{AOB} = 90°$, then

$$\tan = S\frac{b}{a},$$

$$\tan D = \sqrt{a^2 + b^2}.$$

These formulæ are sufficiently simple to permit rapid calculation. However, quicker results may be obtained by a graphic method. The accompanying diagram appears somewhat complicated, because scales for five variables are necessary; but its operation is not difficult. Dotted lines and arrows indicate the solution of an illustrative problem. The components in $AO$ and $BO$ are taken as 4° and 7°, in the directions N. 5° E. and N. 80° E., respectively. Then the angle $AOB$ is 75°. From the point representing 4° on the scale for slope $a$, draw a line through 7° on the inclined scale for slope $b$, intersecting the dummy line. From the point of intersection pass a line through 75° on the horizontal scale marked *angle "AOB,"* to the base of the semi-circular scale for angle $S$. Connect the point of intersection with 75° on the vertical scale marked *angle "AOB."* Through the zero of this scale (the center of the semi-circular scale) draw a line parallel to that previously drawn, intersecting the arc. The reading (in this case approximately 72°) is the angle $S$. Project this point to the same reading (72°) on the vertical scale for angle $AOB$, and from the latter point draw a line to 7° on the vertical scale for slope $b$. The intersection of

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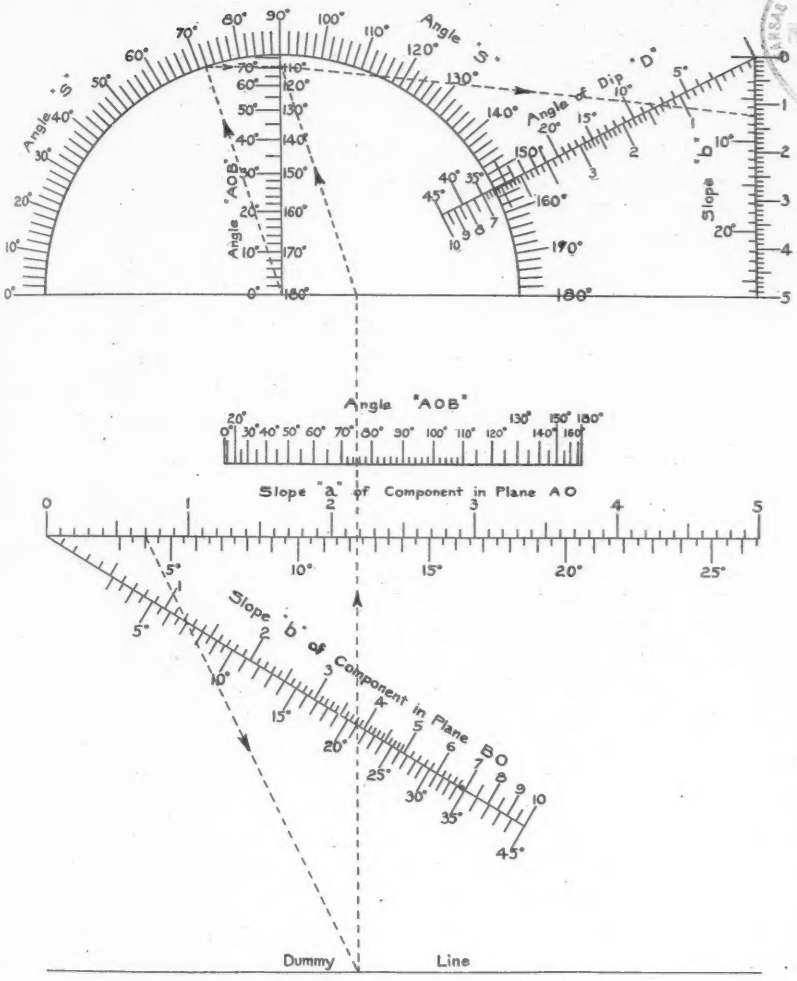


FIG. 27. Diagram for solution of dip problems.

this line with the scale marked *angle of dip "D"* shows the value of the true dip (in this case slightly less than 7° 30′). Using the value of angle *S* (72°) and the direction of component *BO*, the direction of strike is determined as N. 28° W., that of dip as N. 62° E.

If we now solve directly for *S* and *D* by means of the formulæ given above, we obtain 72° 10′ as the value of *S*, 7° 21′ as the amount of dip, *D*. Thus the results check closely enough for all practical purposes.

In this problem the values of the true dip and the larger component differ very little; but the directions are materially different. The case was chosen with this point in view. If the dip of beds is low, components in many directions will have essentially the value of the true dip, and it is seldom possible to determine the strike accurately by direct observation. If the dip is essentially uniform, however, the direction of strike may be readily computed by the method given above.

In using the diagram, it is necessary to start with the smaller dip component; that is, to use *AO* as the plane of the smaller component, and *BO* as the plane of the larger. Unless this is done, the intersection with the dummy line will fall beyond the limits of the diagram as drawn. The angle *S* will always be measured from the plane containing the larger dip component.

It will be observed that the scales for *a*, *b* and *D* have two sets of graduations each. The second set is provided to allow the use of the diagram with units other than degrees. If the dip components are given in feet per hundred or feet per mile, the figures 1, 2, 3, etc., on scales *a*, *b* and *D*, may be used at their face value, or they may be multiplied by 10, 100, or any other convenient factor. Thus, if the dip components *AO* and *BO* were 30 and 50 feet per mile respectively, the graphic solution would start at 3 on scale *a* and pass through 5 on scale *b*. The result, read on scale *D*, would be multiplied by 10 to obtain the value of the dip in feet per mile.

The diagram may also be used for dip problems of other kinds. Thus, if the true dip of beds is 15° in the direction of N. 50° W.,

we may wish to know the component in the direction N. 2° W. Call the plane of this component *BO*. Obviously the direction of strike is N. 40° E., and the angle *S*, between the line of strike and *BO*, is 42°. Draw a line from 42° on the vertical scale marked *angle "AOB,"* through 15° on the scale for *D*. The line intersects the vertical scale for slope *b* at 10°, the result desired. If the strike of beds and one dip component are given, the true dip is readily determined from the diagram.

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# A CONTACT METAMORPHIC IRON-ORE DEPOSIT NEAR FAIRVIEW, NEW MEXICO.

D. D. SMYTHE.

The field data on which this paper is based were gathered during a short period in the summer of 1920 in the course of certain investigations for the Phelps Dodge Corporation. To Mr. P. G. Beckett, general manager of that company, the writer wishes to express his thanks for permission to publish this article.

Time was not available for an extensive survey of the region, and although it has not been possible to make an exhaustive study of the material collected, it seems desirable to place on record such points of geologic interest and such facts bearing on the genetic features of the deposit as have been disclosed thus far, since no detailed description of the region seems to have been made heretofore.

The Iron Mountain iron deposits are located at the northern end of the Cuchillo Mountains in Socorro County, twelve miles north of Fairview, New Mexico. Across the San Augustine Plains, seventy-eight miles to the north, lies Magdalena, the terminus of a branch line of the Atchison, Topeka and Santa Fé Railroad, while some sixty miles to the southeast on the main line of the same railway is Engle.

## TOPOGRAPHY.

The Cuchillo Mountains form a small range of the fault-block type[1] extending nearly north and south, with the Black Range paralleling them on the west, and the San Mateo Range on the east. Between these ranges and to the north and south

[1] Lindgren, Graton and Gordon, U. S. Geol. Survey, Prof. Paper No. 68, p. 220, 1910.

of the Cuchillos lie rolling plains (the bolson plains of Hill[2] and Tight[3]) formed by the filling of intermontane valleys by debris from the mountains. The abrupt change from the rolling valley plains to the steep and rocky mountain slopes is rendered conspicuous by the absence of trees in the filled valleys, while the hills are usually timbered, even if somewhat sparsely in places. The valley floor has an elevation of about 6,000 feet, and the ridges of the Cuchillo Mountains rise at least a thousand feet higher.

Although prospectors have been attracted to these hills for the last forty years, and the iron deposits were discovered over twenty years ago, no producing mines have as yet been developed.

## GENERAL GEOLOGY.

*General.*—The Cuchillo Mountains are made up of a series of eastward dipping Paleozoic limestones, shales, and sandstone, terminated on the west by a large fault. Cutting the sediments are the intrusions of quartz porphyry and andesite porphyry of Tertiary age which are responsible for the formation of the various ore deposits occurring there, but the latter has no connection with iron ores. In the Black Range to the west Tertiary eruptives are much in evidence, but in the Cuchillo Mountains they are nearly lacking since the extensive erosion which resulted in the formation of the valley gravels removed all but a few remnants. During the Pleistocene there occurred an extensive flow of normal basalt[4] which has also been removed from this region except in the vicinity of Fairview.

At the northern end of the Cuchillo Mountains an intrusion of quartz porphyry has apparently arched up the limestone beds, since they dip away from the intrusive. In several places the porphyry has broken through the limestone so as to leave blocks of the latter surrounded by the former. These blocks seem to have been more affected by contact-metamorphic processes than

[2] Hill, R. T., U. S. Geol. Survey. Geol. Atlas Fol. 3, p. 8, 1900.
[3] Tight, W. G., *Am. Geologist*, vol. 36, 1905, pp. 271–284.
[4] Lindgren, Graton, & Gordon, *op. cit.*, p. 283.

the main mass of limestone surrounding the porphyry. They are almost completely changed to garnet and magnetite, while in the limestone surrounding the intrusion the change has been confined to recrystallization or at most the development of a narrow zone of hornfels.

*Paleozoic Limestones.*—The series of limestone beds in which the ore occurs probably belongs to the Magdalena group of the Pennsylvanian as identified by C. H. Gordon[5] farther south in the range. Although the beds were not examined at any great distance from the quartz porphyry intrusion a practically unaltered bluish-gray shaley limestone was found a short distance on either side of the former. It is not definitely known, however, whether the blocks of garnet and ore surrounded by the porphyry, and which as will be shown are contact-metamorphosed limestone, belong to exactly the same beds as those above referred to or to others slightly higher or lower in the series.

*Quartz Porphyry.*—Megascopically, the quartz porphyry is pinkish in color and of variable texture. That at the south end of the area shows abundant phenocrysts of quartz and orthoclase, many of them 3 to 4 mm. in diameter, in a fine-grained ground mass. The porphyry at the north end is much finer grained and shows practically no phenocrysts. Under the microscope the rock is seen to consist mainly of quartz and orthoclase, with subordinate plagioclase, a few crystals of biotite and zircon, and occasional scattered specks of magnetite. The finer-grained rock at the north end is peculiar in that it is composed almost entirely of quartz and orthoclase, the two minerals showing a micropegmatitic intergrowth (Pl. XIV*a*).

*Contact Metamorphism.*—The intrusion of the porphyry into the limestone has in places resulted in a marmorization of the latter, as in the southeast corner of the area mapped (Fig. 28). At other points there is a band of hornfels of irregular width developed in the limestone along the contact. It seems probable that these phases may have developed in limestone beds of different composition. In the marmorized zone there are some

[5] Lindgren, Graton & Gordon, *op. cit.*, p. 262.

isolated lenses of garnet. Their great similarity in mineral character with the blocks that are completely surrounded by porphyry, presents a strong argument that these were once limestone. These masses form three narrow belts within the porphyry, and associated with them are two small patches of hornfels.

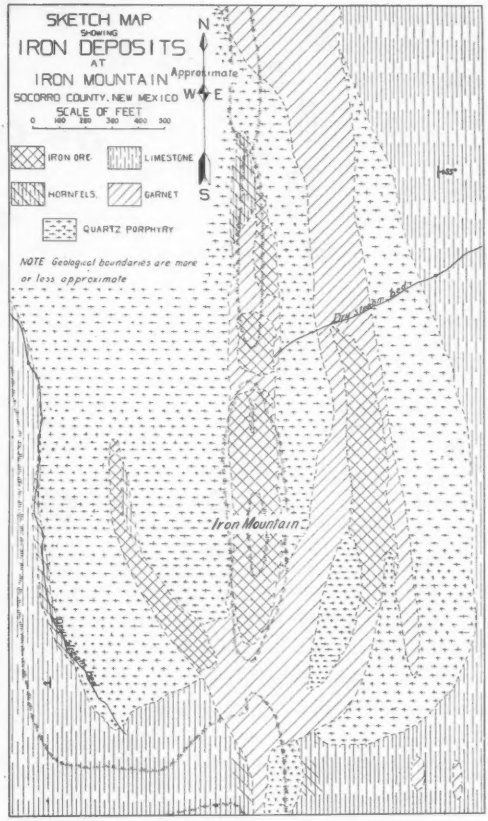



FIG. 28. Sketch map of Iron Deposits at Iron Mountain, New Mexico.

*Hornfels.*—This term is here applied to a variety of contact-metamorphosed limestones which have been developed around the margins of the intrusive. That exposed in the position indicated at the bottom of the map appears, megascopically, to be a white silicified limestone, but a microscopic examination reveals the fact that it is composed of quartz and another mineral, probably andalusite, both of which are filled with minute grains or cloudy masses of epidote. In a somewhat similar development, found at the eastern edge of the western ore body, the andalusite is lacking and the epidote, which is much better crystallized, appears to be of about the same age as the quartz. The area of hornfels marked on the map at the northern end of the middle garnet band, was found to be mainly garnet and epidote with a few grains of quartz and magnetite. At this point the garnet is undoubtedly earlier than the magnetite since the latter is found filling spaces between well-crystallized garnet grains. The epidote is also later than the garnet since it has crystallized in the cracks of the latter and is probably later even than the magnetite judging from other sections in the same area.

Another more peculiar type of hornfels occurs in the bottom of the gulch which follows along the contact at the western edge of the intrusive. The rock in question is very fine-grained and made up of numerous thin light and dark bands which are strongly crumpled (Pl. XIV*b*). These thin bands were found to consist of magnetite, garnet, quartz, and fluorite. This rock outcrops in the bottom of the gulch for a distance of several hundred feet and shows a width of ten to fifteen feet where exposed. The plications may represent a structure developed in what was probably originally a shaly limestone, and were caused by the dynamic force of the intruding porphyry. The difference in the mineral character of the bands, however, is apparently caused by selective replacement by the different minerals. Thus the garnet and magnetite appear to be practically contemporaneous, and to have been deposited first, followed by the fluorite and the quartz. Clusters of specularite foils, crystals of epidote and shreds of more or less bleached biotite are not uncommon.

A few clusters of radiating needles of some colorless, undeterminable silicate were also noticed.

Similar structures have been noted by Bergeat,[6] Kemp,[7] Spurr,[8] and Stewart.[9]

It is possible that in the case of the hornfels composed chiefly of quartz, andalusite, and epidote, that some of these minerals might be due to a reorganization of the elements of the shaly limestone, but one cannot avoid the thought that the magmatic waters from the intrusive also contributed some material.

*Garnet-magnetite Rock.*—This consists chiefly of a granular mixture of garnet and magnetite varying in all proportions from pure garnet to almost pure magnetite. As stated above it is developed almost entirely in areas which are completely surrounded by porphyry and is supposed to be a contact-metamorphosed limestone, that has been entirely replaced. Genetically it is closely related to the hornfels. On the accompanying map (Fig. 28) a line has been drawn separating the garnet rock from the ore but this must not be mistaken for a definite boundary since in the field there is a gradual change from one to the other.

SEQUENCE OF CONTACT-METAMORPHIC MINERALS.

*Green Garnet.*—The first minerals to form in the contact metamorphosed area were yellowish-green garnet and magnetite. The periods of deposition of the two seem on the whole to have been contemporaneous, but in some sections the garnet can be seen cutting the magnetite while in others the garnets seem to have crystallized earlier. This would tend to indicate a fluctuation in the character of the depositing solutions as would also the zonal growth of the garnet (Pl. XIV*c*) and the magnetite (Plate XIV*d*). No chemical analysis was made of the garnet but judging from its appearance and associations it is quite probably andradite. Much of the garnet is massive but in many

[6] "Die Erzlagerstätten," 1906, p. 1145.
[7] *Amer. Inst. Min. Engrs., Trans.*, XXXVI., pp. 191 and 198.
[8] U. S. Geol. Surv., Prof. 55, p. 39, 1906.
[9] *Amer. Inst. Min. Engrs., Trans.*, XLIII., p. 240, 1906.

cases it shows well formed dodecahedrens. As is often the case with andradite formed under these conditions the garnet shows anomalous double refraction (Pl. XIV*c*).

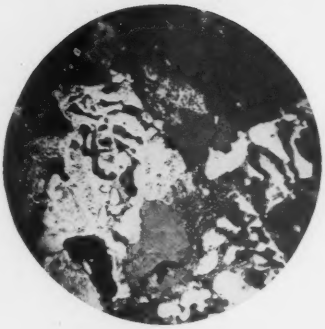
*Magnetite.*—Most of the magnetite is fine grained and massive, but occasionally it shows well developed octahedrons. The magnetite of this region shows with remarkable clearness the process of change to hematite. This may be seen along the cracks and octahedral planes, but the replacement has not been uniform throughout the deposit; Pl. XV, *a, b, c, d,* shows the steps in the change from nearly unaltered magnetite to nearly pure hematite. It is possible that the reaction took place during a late stage by the ascending solutions, for a few hematite needles were formed as one of the latest developments in the crumpled hornfels previously mentioned. The writer is however inclined to favor the explanation given by Lindgren for the formation of hematite from magnetite by descending solutions at Daquiri, Cuba.[10] Although this theory seems quite probable in view of the dry climate it could not be substantiated since no ore from below the zone of weathering could be examined.

*Hedenbergite.*—Subsequent to the garnet-magnetite period of deposition came the formation of hedenbergite which is found only in the small patch of hornfels at the north end of the large central ore body. This hornfels is a dark, greenish-black rock which upon microscopic examination is found to consist mainly of well crystallized hedenbergite. Rounded particles of garnet are included in the hedenbergite as well as rusty spots which probably represent remnants of some mineral which has been almost entirely replaced by the hedenbergite. The latter is in turn altering to a dark blue amphibole, which on account of its imperfect crystallization could not be definitely determined but is probably close to arfvedsonite in composition.

*Feldspar.*—Following the hedenbergite came a series of minerals whose relations to each other are not always clear. Probably the first of these was feldspar, several varieties of which

[10] *Amer. Inst. Min. Engrs., Trans.,* LIII., p. 55, 1915–16.

P



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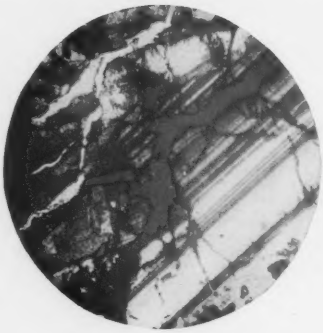

*c*

*d*

*a*. Section showing micropegmatitic intergrowth of quartz and orthoclase in quartz porphyry. White orthoclase, black quartz. x-nicols. × 110.

*b*. Section of hornfels showing thin bands of magnetite, garnet, quartz and fluorite. × 17.

*c*. Section showing zonal garnet and magnetite (black). x-nicols. × 90.

*d*. Polished surface showing zonal structure of magnetite after etching with hot hydrochloric acid. × 75.

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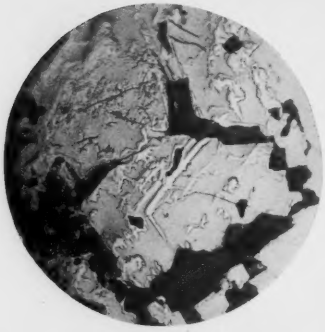

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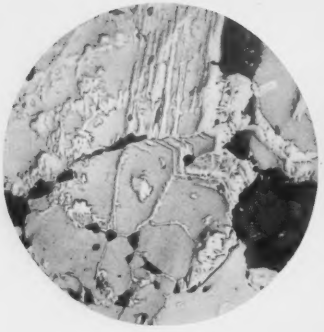

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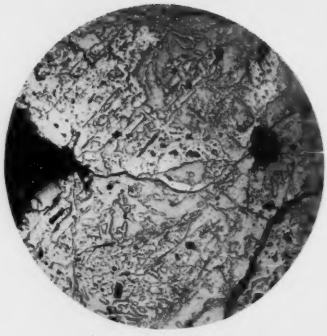

*d*

*a*. Polished surface of ore showing first stage in change of magnetite to hematite along cracks. × 420.

*b*. Same as *a*, but showing more advanced replacement of magnetite by hematite. Black, gangue minerals. × 105.

*c*. Same as *a*, but representing a still more advanced stage in the change of magnetite to hematite. Black gangue minerals. × 105.

*d*. Polished surface of ore, with magnetite nearly all changed to hematite. × 64.

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are seen at different points. In one specimen examined the magnetite was found to be cut by a veinlet of badly altered plagioclase, apparently labradorite, which was itself cut by a veinlet of later fluorite. At a number of places in the hedenbergite rock, orthoclase was found and a few grains of twinned feldspar, perhaps labradorite.

*Quartz and Fluorite.*—These two minerals appear to have formed at nearly the same time and later than the previously mentioned minerals. Both are found widely distributed through the deposit and are in places quite abundant, pieces of fluorite being obtained which were several inches in diameter. The mineral sometimes found in the hornfels and called andalusite also probably belongs to this period. It does not appear however in the magnetite-garnet deposits.

*Epidote.*—Epidote is of frequent occurrence but always in small amounts. Where associated with garnet its later development is shown by its position in the cracks of the former and where with quartz and fluorite it appears either of the same age or slightly later than these two.

*Hematite.*—Needles of specularite were found associated with epidote in the fluorite of the crumpled hornfels. They appear to be of nearly the same age as the fluorite and may have been developed from the magnetite already present. The hematite occurring as an undoubted alteration product of the magnetite is apparently massive, indicating that the solutions producing the change may have been cold. Whether these altering solutions came from below or above must remain in doubt until the deposits have been more fully developed.

*Malachite.*—A few specks of malachite were noted in one of the hand specimens and doubtless represent the oxidation product of some copper sulphide, although none was seen in the rocks examined.

*Calcite.*—Calcite does not appear to have been deposited from the ascending solutions since it usually occurs not far from unaltered limestone where it probably represents the recrystallized remnants of the latter.

## SIZE AND SHAPE OF ORE BODIES.

The garnet zones (Fig. 28), in which the ore has developed, consist of three nearly parallel bands which join near the southern edge of the map. There is more or less magnetite throughout the whole mass of the garnet rock but only those portions in which the garnet is subordinate have been designated as ore. There are three large ore-bodies, one in each of the three bands of garnet (Fig. 28), and two smaller ones which are really a continuation of the central ore-body since they are separated from it only by garnet rock, which has not quite enough iron to be classed as ore. As exposed at the surface the main ore bodies are roughly lens shaped, varying from 60 to 250 feet in width and averaging 1,200 feet in length. No idea could be formed as to their extension in depth since, aside from a fifty foot tunnel there are no underground workings. It seems possible however that they will not extend over a few hundred feet in depth since the strongest metamorphic action appears to have been confined to the roof of the intrusion.

## SUMMARY.

The Paleozoic limestones of Iron Mountain have been intruded by a quartz porphyry. This intrusion has resulted locally in contact-metamorphism of the limestone. These effects are shown by the development of (1) marmorization of the limestone, (2) hornfels rocks of varied character, and (3) granular aggregates of garnet and magnetite.

In addition to the sequence of the metamorphic minerals mentioned above, a most interesting feature is the change of the magnetite to hematite, which can be seen in all stages of development.

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# DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

## *GRAPHITE OF SLEAFORD BAY, AUSTRALIA.*

*Sir:* It is with much interest and satisfaction that I have just read Mr. Tilley's article in the Number 3 of this Journal (vol. 16, pp. 184–198), especially as it contained a recognition of the mode of origin of graphite set forth in my own paper in the same number. In his consideration of the possible sources of the carbon now crystallized as graphite, he writes on page 194, "the silication of the limestones would supply enormous quantities of carbon dioxide which would be available for deoxidation." And on the next page occurs the following: "It seems highly probable that . . . the sediments themselves must be considered as the ultimate source of the carbon of bituminous material contained in these or the carbon chemically combined in calcite and dolomite, and released as carbon dioxide during the contact metamorphism." However, no effort is made to support the latter possibility, nor is it given any weight in the general summary on page 198. Without wishing to be considered a special pleader, the present writer would call attention to certain associations mentioned by Mr. Tilley which seem to show that the graphite of Sleaford Bay need not be wholly organic in origin.

Mr. Tilley describes garnet crystals from the coarse graphite gneisses which exhibit a zonal structure—a center of pink garnet, a dark intermediate zone characterized by inclusions of graphite,

and an outer shell of clear pink garnet. Evidently this included graphite was crystallized while the garnet was forming. We are not told the composition of the garnet, but presumably it is a product of the silication of the dolomites. As for the origin of this graphite, the contention that it was derived from carbonates by silication is preferred, for this process provides a source perfectly competent to supply all of the graphite present. The view that it is of organic origin is not supported by independent evidence.

Mr. Tilley has given equations in an earlier paper which show that the production of forsterite, edenite or diopside from dolomite involves the formation of calcite (except in the case of diopside) and of $CO_2$. In the process of complete dedolomitization, diopside is considered the final product. This process involves the elimination of the $CO_2$, in so far as siliceous or aluminous material can be found to complete the appropriate chemical reactions. This is essentially one of the results of the metamorphism of all carbonate rocks in which tremolite, diopside, wollastonite and scapolite are formed. In all such cases of metamorphism we have the formation of residual $CO_2$.

The problem, as I see it, is two-fold. In the first place, is the chemical setting appropriate for the transformation of this residual $CO_2$ to graphite? Secondly, is there sufficient $CO_2$ evolved to form the graphite now known to exist in the rocks? It does not appear that as much graphite as 10 per cent. is incompatible with the view that it was derived from the carbonates of the original rock, for 10 per cent. graphite (assuming it to be pure carbon) would demand an original content of 37 per cent. $CO_2$, or of 83 per cent. calcite, or of 77 per cent. dolomite. Alling states that 5 per cent. graphite is a fair average for graphite ores.

It is entirely a problem as to how it can be done and not one as to whether it can be accomplished. The geological setting consists primarily of carbonates subjected to a metamorphosing influence, and of the inability of the oxides of carbon to escape. In the formation of graphite we are still confronted with the

problem of the fate of the oxygen, but that element usually takes good care of itself, and its absence needs no explanation. The problem of "fixing" the carbon is of prime importance, and this is true whether the graphite be considered directly organic or not.

The solution of this problem will ultimately be found in works rich in petrographic detail, such as Mr. Tilley's recent papers. Further research in his distant field will doubtless yield a wealth of detail corroborating known results and perhaps supplying new facts. We hope soon to hear from this author again.

I would take this opportunity to emphasize again that the formation of graphite appears to be the result of uncommon conditions. Of all the known metamorphosed sedimentary rocks only a small percentage carry graphite, and in the absence of collateral evidence we cannot assume that the presence or absence of graphite in the crystalline rocks implies the presence or absence of organic matter in the original sediment. Moreover, even if the origin of graphite from the carbon of silicated carbonates be accepted, we must still face the situation that in only an infinitesimal percentage of cases do the contacts between intrusives and sedimentary rocks carry graphite.

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DEPARTMENT OF GEOLOGY,
HARVARD UNIVERSITY,
CAMBRIDGE, MASS.

# REVIEWS

**Field Methods in Petroleum Geology.**—By G. H. Cox, C. L. Dake, and G. A. Muilenburg. First edition. 305 pages, 50 figures, 11 tables and charts. Flexible pocket size, 5″ x 7-½″. McGraw-Hill Book Company. Jan., 1921. Price, $4.00.

This technical book represents in a direct and simple manner the special methods of structural mapping most commonly applied by petroleum geologists of good judgment and engineering ability. Although its focus of interest tends to be in central United States, the methods employed involve sound principles of engineering accuracy applicable to any other prospective petroleum region. Although apparently considered by the authors as a "discussion of the minutiae of field procedure, as it applies to this highly specialized branch of engineering geology," these principles may be employed not only in petroleum investigations, but in many other types of geological work.

The authors infer that the reader has "a knowledge of general geology and lithology" and present the book as a series of "discussions of field methods, since most of the field work has to do with the location of structural features." Following a twelve page introduction, in which "are summed up briefly and concisely the various methods of oil accumulation, as they are ordinarily conceived," are Chapter I., *Instruments,* Chapter II., *Instrument Methods,* Chapter III., *Identification of Structure,* and Chapter IV., *Field Operation,* including a *Glossary.* These chapters, comprising pages 13 to 227, are followed by a sixty-five page *Appendix,* containing tables, charts, etc., essential to surveyors.

Chapter I., in describing "the instruments commonly used in the field work of the petroleum geologist," begins the discussion with *level vials,* followed by detailed descriptions of the history, use, care, adjustment, and parts of the *compass,* especially the Brunton; *hand levels* (Locke, square, Abney, Gurley monocular and binocular, Bausch and Lomb prismatic binocular); *barometers,* special stress being laid on the aneroid; the *alidade,* the Gale type especially; *leveling and stadia rods;* the *plane table,* and concludes with a description of the kinds of paper used on the plane table.

Chapter II., on "instrument methods in general use," discusses (1) determination of direction, (2) determination of distance, and (3) de-

termination of elevation, the last of which is taken up in greatest detail, while the first is stated only briefly. Under the second division, pacing, buggy wheel, and automobile traverses are considered from a practical viewpoint; intersection, and resection methods are discussed, and instrumental methods are given most consideration—the methods of stadia, gradienter screw, vertical arc and Beaman stadia arc. In the determination of elevation, the methods in use of the aneroid barometer are first discussed, from the standpoints of observation and correction. The methods in the use of the hand level and clinometer are then briefly given. The last fifteen pages are devoted to the methods of use of the alidade, simple leveling, stepping or intercept, computed step, vertical arc, Beaman stadia arc, gradienter screw, stadia wire, intersection and vertical angle, and backsight methods.

Chapter III., on "the various geologic criteria that are used in correlating beds and identifying structures," takes up the most important subject in the book, as far as geological interpretation is concerned. It begins with general considerations of the discussion, then passes on to identification of strata, or stratigraphic correlation; following this are a few paragraphs on dip, while the remaining and greater part of the chapter is devoted to "aids in recognizing structure," under the following headings: abnormal regional dip, wavy conditions, fracturing, lines of folding, dip slopes, erosion escarpments, valley profiles, topographic highs, break overs, radiating drainage, bends in streams, side on which tributary streams occur, rough topography, inliers and outliers, soil, float, water seepages, springs, vegetation, oil and gas seepages, faults and their recognition, where to look for outcrops, and outcrops of the oil sand.

Chapter IV., "devoted to the personnel of the field party, to the actual field procedure in reconnaissance and detailing, and to the preparation of the map and final report," might well be designated as *geological efficiency in the field*. This chapter is clearly expressed and interesting. It is divided into the following parts: (1) the field party, (2) reconnaissance work, (3) detailed survey, (4) making the field map, (5) keeping of the notes, (6) the finished map, and (7) the final report. The latter part of the chapter is devoted to a glossary of various specialized technical terms, both geological and instrumental.

The tables included in the appendix are as follows: I. Natural functions. II. Reductions of stadia observations for rod readings. III. Stadia tables for obtaining differences of elevations (including an explanation), and conversion of feet to decimals of a mile. IV. Gradienter table for the determination of distances. V. Table for determining horizontal distances by means of the vertical arc. VI. Temperature

corrections for altitude scales (with explanation). VII. Airey's table for the determination of altitude by means of the barometer. VIII. Conventional signs. IX. Table of eras and periods. X. Land surveys. XI. Isogonic chart. Upon this last chart it might have been well to have graphically explained how to set off declination on a compass, for it is often a misleading procedure.

The book as a whole is well organized, clearly expressed, and contains most of the specialized necessities for this particular type of work. The fact that it is centralized and concentrated for one purpose will doubtless make it a useful book for beginning geologists who enter this field, and should help to emphasize the necessity of a high standard of work.

On page 178 is stated "In many cases reconnaissance work will show that no favorable structural conditions are present, or there are not sufficient outcrops to warrant an effort to make a detailed map." I have seen cases, in the southern Appalachians in particular, where competent geologists in reconnaissance work came to this latter conclusion, but when detailed work was later done sufficient data were found to solve conclusively the structure.

A book of this size is limited materially in the information it should contain. Methods used in foreign fields and in some of our western states and in out-of-the-way places in various parts of North America, often differ widely from the methods discussed in this book. Ingenuity in adapting other types of surveying methods to other kinds of geological conditions than are dealt with here should, perhaps, be more strongly emphasized.

The figures presented, are on the whole, good. The photographs, however, are not printed on suitable paper to bring out their full value for a book of its price. Additional illustrations might well have been included to bring out more clearly different features discussed, such as the important subject of outcrop dips.

Half of the book is given up to the subject of instruments, and only 36 pages to identification of structure, which is really the point upon which focus should be maintained.

The study of subsurface conditions, such as those available through well data, is not considered by the authors within the province of the book. It should be considered, however, in relation to field work, especially in correlation, wherever such data are available.

Greater stress could well have been placed upon note taking, and note and map organization relative to the final report. Although the final report is in the province of the office, its organization should be developed systematically during field work.

The subject of management and direction of field work in geology has not been given much consideration. This subject is becoming more and more important as geologists of varying degrees of ability are assuming positions of directorship and management.

On the whole the book represents an excellent and well worth while publication. All those who are engaged in the training and direction of young geologists will appreciate this work. It is instructive and interesting. It is a handy reference and a good text to follow.

OLAF P. JENKINS.

STATE COLLEGE OF WASHINGTON,
PULLMAN, WASH.

**Prospector's Field Book and Guide.** By H. S. OSBORN and M. W. von BERNEWITZ. Ninth Edition, 1920. Pp. 364. Figures 55. New York, Henry Carey Baird & Co. Price $3.00.

The ninth edition of Osborn's "Prospector's Field Book and Guide," revised and enlarged by M. W. von Bernewitz, is a well-written and useful volume. Its purpose is to aid the prospector in his search for mineral deposits and in his investigation of them.

Following a short introduction is a chapter of elementary mineralogy and geology, of doubtful value to the technically trained man, who, it is admitted, is the best fitted for present-day prospecting. The same may be said of the chapters on crystallography and surveying. However, the following section, dealing with ore analysis, is a well-condensed and useful one. Likewise, the ten or eleven remaining chapters, which contain clear and precise accounts of the occurrence, production, character, and uses of all the metallic and non-metallic ores and of petroleum, are veritable mines of needed information for the prospector. Each chapter also gives detailed determinative tests for the minerals of which it treats. In the appendix are tables of weights and measures, and a description of the unit system of buying and selling ores. The book is fully indexed. Its illustrations, though too few in number, are good. It is well printed, bound in flexible leather, and of a size to be conveniently carried.

C. H. JOHNSON.

# SCIENTIFIC NOTES AND NEWS[1]

H. G. FERGUSON, of the U. S. Geological Survey, has been acting as chief of the division of geology and of the section of metalliferous deposits in the absence of F. L. Ransome.

J. S. DILLER, of the U. S. Geological Survey, has finished his field work in the Lassen Peak area and has returned to Washington.

ALEXANDER RICHARDSON, principal of the Camborne School of Mines, Cornwall, was recently a visitor in New York.

OLAF P. JENKINS, of the Washington Geological Survey, has been in western Washington, making an examination of iron-ore resources.

WILLET G. MILLER has been visiting the Sudbury district of Ontario.

W. H. EMMONS has returned from Manchuria to Minneapolis.

BRUCE ROSE, geologist to the Whitehall Petroleum Company, has completed his investigations in Canada, and has returned to London. He will leave shortly for Assam.

A. H. BROOKS completed a geologic investigation in the Kantishna region, Alaska, in September, later going to southeastern Alaska for geologic work, and is now in Washington.

WALDEMAR LINDGREN has returned from Bolivia, where he has been for the past few months.

E. P. MATHEWSON sailed from New York for Burma, on September 22.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

H. L. SMYTH, Professor of Mining at Harvard, spent the summer in Michigan, as consulting engineer to the Cleveland-Cliffs Iron Co., of Ishpeming.

L. C. GRATON, of the Department of Geology, Harvard, and B. S. Butler, of Calumet, Michigan, have been carrying on a geological investigation in Cobalt to determine if there is any relationship between the deposits of native copper in Michigan and native silver in Cobalt.

EARL H. YOUNG has been appointed Professor of Geology in the Montana School of Mines.

GEORGE S. RICE, of the U. S. Bureau of Mines, has returned from a trip of inspection of coal property in Alaska.

CHESTER W. WASHBURNE, geologist, has returned to New York from South America, where he spent eight months in the examination of oil properties.

E. P. MATHEWSON has been appointed consulting engineer to the Burma Mines, Ltd., of London.

WILLARD JILLSON, of Frankfort, Kentucky, and Director of the Kentucky Geological Survey, received the doctorate (Sc.D.) from Syracuse University at its fiftieth Commencement last June.

JOHN T. REID recently left New York for his office in Lovelock, Nev. He expects to return to New York in January.

J. EDWIN HAWLEY, of Kingston, Ont., has returned from Ecuador, where he has been investigating oil lands. He has now left for India to make geological investigations.

F. W. GRAY has joined the staff of the British Empire Steel Corporation at Montreal, after resigning as editor of the *Canadian Mining Journal*.

F. H. MOFFIT, S. R. CAPPS, C. P. MCKINLEY, AND R. K. LYNT, with their field parties, arrived in Washington from southwestern Alaska, in September.

G. W. CRANE has opened an office as consulting geologist at Salt Lake City. He is still associated with the Chief Consoli-

dated Company, to which company he has been geologist for several years.

J. D. NORTHROP has been assigned to the mineral division of the Land Classification Board of the U. S. Geological Survey. For the last two years Mr. Northrop has been doing private petroleum geological work.

WALTER E. CAMERON, formerly Deputy Chief Government Geologist, Geological Survey of Queensland, and Chairman of the Committee on Development of Oil and Gas at Roma, has been appointed Mining Geologist to the Federated Malay States Government and has commenced his new duties at Ipoh, Kinta District, Perak.

G. C. MARTIN has returned to Washington after a summer's work in Alaska for the U. S. Geological Survey.

H. FOSTER BAIN was recently in Berkeley and Bakersfield, Cal.

H. M. EAKIN is completing geologic work in the vicinity of Juneau, Alaska.

C. P. MCKINLEY, of the U. S. Geological Survey, recently returned from Alaska, and will work at the Sacramento office of the Survey this winter.

H. A. GUESS has returned to New York from a trip to the Premier Mine in British Columbia.

DORSEY LYON, of the U. S. Bureau of Mines, has returned from Alaska, and is at present in San Francisco.

FRED B. ELY is making examinations for oil and gas in western Mexico.

M. J. KIRWAN, petroleum engineer, and F. X. Schwarzenbek, assistant petroleum technologist of the Bartlesville station, are in the Deaner field in Oklahoma, investigating underground conditions.

DEAN W. R. APPLEBY, of the Minnesota School of Mines, has returned to Minneapolis after a three months' trip through Japan, Korea, and Manchuria.

E. H. WELLS, who conducted special geological investigations for the Chino Copper Company, of Santa Rita, N. M., in 1920 and this year, is the new president of the New Mexico State School of Mines at Socorro. Since 1918 he has been professor of geology and mineralogy and still occupies this chair. C. W. Vanpell, recently of the geological staff of the Anaconda Copper Co., at Butte, has also been added to the faculty.

B. B. GOTTSBERGER has been elected secretary of the Mining and Metallurgical Society of America.

OWEN LETCHER, editor of the *South African Mining and Engineering Journal,* has gone to India on a three months' visit.

WELTON J. CROOK has been in Oregon examining deposits of iron ore.

W. H. GOODCHILD, of London, is at Kirkland, Ontario.

G. F. LOUGHLIN, of the U. S. Geological Survey, has recently spent a few days at Yale University, New Haven, Conn., going over data pertaining to the geologic report on Leadville, Colo., now in preparation for publication by the U. S. Geological Survey.

H. EARL HAVENOR has resigned as geologist to the Tintic Standard Company at Eureka, Utah, and will open an office at Salt Lake City.

E. F. BIRCH, manager of the Knight properties in the Tintic district, has resigned. Hugh Trenholm will be his successor.

J. NELSON NEVIUS has been appointed temporarily instructor of geology in the California Institute of Technology at Pasadena.

C. C. LEACH has been elected president of the North of England Institute of Mining and Mechanical Engineers for the coming year.

A. W. AMBROSE, chief petroleum technologist for the U. S. Bureau of Mines, is making an extended trip in the West, visiting oil wells on the public lands.

M. G. GULLEY has been examining the geologic structure in the Elk Basin oil field of Wyoming.

CHARLES A. RICHARDSON, manager of the Chambers-Ferland mine, Cobalt, has sailed for London.

E. F. NEIMAN, general superintendent of the Harmony Mines Co., Baker, Idaho, and J. F. Inglis have opened an office at Salmon City, Idaho, where they will conduct general consulting work in geology, mining, metallurgy, and mill design.

THE FIELD MEET of the Association of State Geologists took place this year in Tennessee from October 7 to 15. Trips were scheduled to a number of places of geologic interest throughout the state, including Mt. Pleasant phosphate mines, the Ducktown copper mines, the Mascot and Embreville zinc deposits, the Cranberry magnetite deposits, and marble and clay deposits.

THE ANNUAL MEETING of the Society of Economic Geologists will be held, in conjunction with the annual meeting of the Geological Society of America, at Amherst College, Amherst, Massachusetts, December 28–30, 1921.

The Society of Economic Geologists held the first of its semi-annual meetings in conjunction with the American Institute of Mining Engineers at Wilkes-Barre, Pa., on September 14. The meeting was very successful and surprisingly well attended. The following papers were presented: Some unique Bolivia tungsten deposits, by F. L. Hess; The occurrence of zinc and lead in Pennsylvania, by Benjamin L. Miller; General geology of the Catorce Mining District, by C. L. Baker; Relation of gypsum supplies to mining, by D. H. Newland; Geology applied to ore hunting, by Augustus Locke; Deep-seated oil and gas in the Appalachians, by George H. Ashley; The structure of the anthracite region, by J. F. Kemp; Coning of water in the Mexican Gulf Coast wells, by E. DeGolyer.

GEORGE OTIS SMITH has returned to Washington after attending the meetings of the organization committee of the Twelfth Session of the International Geological Congress which is to be held in Belgium next year. He reports that the following resolutions were submitted:

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1. That the International Geological Congress should be continued, modified to meet present conditions.

2. That the question of the establishment of an international Geological Union should be considered at the next International Geological Congress and that it is undesirable that any steps should be taken until the question has been so considered at a full and representative gathering of geologists.

3. That the organization of the Congress shall be as simple as possible consistently with securing continuity of effort from one Congress to another.

(The representatives of Great Britain, United States and Canada reported that the feeling of the geologists of their respective countries was overwhelmingly in favor of an organization along the lines of the International Geological Congress.)

4. That the above resolution be communicated to the President of the Geological Society of London, the Secretary of the Royal Society and the Secretary of the Belgian organization committee of the next International Geological Congress.

The Committee also drew up proposals with regard to a constitution to be submitted for the consideration of the next International Geological Congress.